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RF CHARACTERISTICS OF MICA-Z WIRELESS SENSOR NETWORK MOTES

by

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RF CHARACTERISTICS OF MICA-Z WIRELESS SENSOR NETWORK MOTES

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This thesis studies the RF characteristics of Mica-Z wireless unattended sensor networks for military and commercial applications. Several experimental configurations were designed and experiments carried out to observe and analyze the behavior of the Mica-Z sensor network. The Mica-Z mote's propagation characteristics and network performance were measured under near free space, indoor and outdoor environments to provide a comprehensive perspective of typical sensor network characteristics. Link-break and re-association distances with their corresponding RF power measurements were recorded to determine the Mica-Z's range characteristics under these different operating environments. Power loss exponents were also estimated to provide Mica-Z users a faster and more convenient way to estimate operating ranges in the different environments. A graphical numeric electromagnetic code (GNEC) simulation was also used to investigate some of the possible improvements that could be made to the existing Mica-Z antenna design to enhance the performance of the sensor network. This thesis substantiates the difficulties of operating such sensor networks in the most hostile environments. Although the measurements and analyses demonstrated that controlled deployment was possible to some extent, the effectiveness of deployment remains challenging especially for random ad-hoc deployment.

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EXECUTIVE SUMMARY

Wireless sensor networks are an emerging technology made up of small wireless sensors which are smart enough to communicate effectively with other sensors nearby. The success of this technology can only be made possible by the combined evolution of integrated circuit technologies, data networking and wireless communication. These fields continue to achieve breakthroughs in reducing the size, weight and cost of the sensors while at the same time improving the fidelity and reliability of the sensors. While many technological limitations have been overcome, there remain many other challenges to be resolved before we can see extended applications of wireless sensor networks in more demanding environments. The Mica-Z network sensor is one good example of this situation where its operation has proven to be functional but the underlying deployment limitations continue to be problematic and a hot topic of research in many academic institutions. It is the intent of this thesis to study the physical layer characteristics of Mica-Z sensor network motes upon which all the other layers in the protocol stack of wireless sensor networks are critically dependent. These characteristics are critical parameters which any network designer using Mica-Z sensors will need to produce a practical and reliable design.

In this thesis, the antenna and power characteristics of the Mica-Z sensor were investigated. In the study of antenna characteristics, the voltage standing wave ratio (VSWR) and radiation patterns were measured. In addition, the graphical numeric electromagnetic code (GNEC) modeling program was used to simulate some simple antenna models which could raise the performance of the sensor in terms of antenna gain and half power beamwidth. The simulation models built include top-looped, top-loaded and turnstile antenna design and the results were compared with the original Mica-Z antenna design as the baseline. The results have indicated that each model has its own advantages and is suitable for different applications depending on the operating environment.

In the study of Mica-Z power characteristics, receive power measurements for near free space, indoor and outdoor conditions were taken and evaluated. Path loss exponents for these three conditions were also derived to provide the user with a good feel of how the Mica-Z network sensor behaves electromagnetically under different environmental conditions. In addition, measurements of battery voltage versus the operating range and power were also carried out to verify their relationship. The main highlight of this result is the high sensitivity of the operating range to battery voltage, which may potentially cause major sensor network design discrepancies if not taken seriously.

The results obtained from the study of the characteristics of the Mica-Z sensor networks demonstrated their lack of deployment feasibility. This is illustrated in some of the many discussions and analyses made in this thesis. It is likely that all the noted challenges will be overcome in the near future due to technological advancements and intense research interest. However, further advancements are impossible without a good understanding of the antenna and power characteristics of the network sensor. This thesis is designed to provide a practical baseline for such future studies in the area of wireless sensor networks.

I. INTRODUCTION

In recent years, new technologies have shaped numerous military and commercial strategies in an unprecedented way. The Wireless Sensor Network (WSN) technology is one such technology and has been attracting significant attention. WSN provide a promising infrastructure for gathering information about parameters of the physical world which can be subsequently processed for both commercial and military applications [1].

The increasing miniaturization of RF devices and microelectromechanical systems (MEMS) coupled with advancements in wireless networking have enabled a new generation of massive-scale sensor networks suitable for many applications. These have inspired numerous research investigations in the area of wireless sensor networks (WSN) [1].

In the new generation of large-scale sensor networks, sensors will normally be employed in miniature autonomous devices known as sensor nodes to form the network without the aid of any established infrastructure (ad-hoc topologies). The individual nodes are capable of sensing their environments, processing the information locally, and sending it to one or more collection points through a wireless link. Each node normally has low RF transmit power which helps in prolonging the lifetime of the battery. This is necessary because the sensor nodes in many applications are mostly inaccessible, thus requiring the sensors to operate without battery replacement for a long time [1]. Such conditions make the RF channel and power consumption characteristics a critical factor in the sensor network system design and deployment. It is important to have a good understanding of these characteristics as such factors ultimately affect the WSN operating characteristics (such as available range, battery lifetime, antenna design, etc.), cost and deployment feasibility.

This thesis is devoted to the study and understanding of basic RF characteristics of such sensors. Crossbow Mica-Z sensors were chosen for this study as it was Crossbow's newest product and this is commonly used by researchers.

A. OBJECTIVE

The objective of this thesis is to provide a fundamental understanding of the Mica-Z sensor networking system. It involves the investigation of RF characteristics of Mica-Z wireless unattended network sensors in different applications.

To conduct the study, several measurement setups were designed and used to collect RF power received measurements under near free space, indoor and outdoor environments. The data collected has been discussed and analyzed in depth to provide a comprehensive perspective of such sensor network characteristics.

RF power receive measurements were recorded and analyzed to determine the Mica-Z's range characteristics under three different operating environments. Power Loss exponents were calculated to provide Mica-Z users a faster and easier means of estimating operating ranges under such environments.

Battery performance was also investigated under the near free space environment with respect to the break and re-associate distances. A relationship between the battery voltage and break and re-associate distance is established to demonstrate the effect of battery power on the operating range.

GNEC simulation was used to investigate some of the possible improvements that could be made to the existing Mica-Z antenna design to enhance the performance of the sensor network.

This study is necessary in providing an overview on how such sensors behave under different environments, and the results collected from the

measurements will help to set the baseline for future development and deployment of the Mica-Z mote in WSN applications.

B. ORGANIZATION

This thesis is organized into several chapters. Chapter II provides an overview of wireless sensor networks. Chapter III delves into the RF characteristics of the Mica-Z antenna: the VSWR, radiation pattern and effects of antenna configuration. GNEC simulation software was used to investigate the possible improvement of the existing Mica-Z antenna design. Chapter IV provides an overview and results from a variety of measurements to determine the power and range performance under different operating environments. The measurements were designed to measure network performance under three different scenarios, namely the near free space, indoor and outdoor environments. Chapter V provides conclusions and recommendations for future research.

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II. WIRELESS SENSOR NETWORK

Wireless Sensor Networks (WSN) are an interdisciplinary research area that draws on contributions from signal processing, networking and protocols, databases and information management, distributed algorithms, and embedded systems and architecture. WSN can be used for many military and commercial applications, and in many of these applications the size of nodes, RF behaviors and energy consumption rate are the keys factors in designing WSN [2, 3, 4]. This chapter provides an overview of WSN including node characteristics, WSN architecture and communication protocol. In the communication protocol, more emphasis is placed on the physical layer of the network model where the majority of the subject interests of this thesis lie. Finally, technical overviews of the Crossbow Mica-Z wireless network sensors will be discussed.

A. CHARACTERISTICS OF WIRELESS SENSOR NETWORKS

Wireless sensor networks consist of devices that combine the functionality of sensing, computation and communication into a single device capable of self-organization and inter-device connectivity. Each sensor node in the WSN is capable of self-organizing its functions into proper working order. The node has the ability to sense the physical environment and communicate this information to the allocated base stations and nearby secondary nodes. Wireless sensor networks are typically highly distributed and their characteristics are typically self-organizing, low power and lightweight in design resulting in a wide diversity of uses [2, 3, 4].

The network sensor's ability to self-organize is necessary to synchronize network operations among the sensor nodes themselves and between sensor nodes and base stations. It allows for unattended wireless sensor network operation and it is incorporated mostly in software. In both military and commercial network applications, users place high regard on the network

sensor’s ability to adapt to the dynamic network environment and it is this self-organizing capability that determines the reliability and scalability of any wireless network sensor [2, 3, 4].

Low power operation of the sensor network is another characteristic that has vast implications on the performance of a network sensor. Network sensors are often required to be deployed in an environment where access to the network sensors is nearly impossible and the battery replacement for such network sensors is impractical. In such a situation, low power operation is necessary to reduce any chance of mission failure as a result of insufficient battery life. The battery life requirement is normally application specific, and typically two to four years is desirable. There are typically two ways to control the battery life. The less direct way is by finding a means to optimize the network sensor operation such that the power requirement is minimized. One good example would be the sleep mode operation: the sensor turns itself off when nothing is sensed. A more direct way is the improvement of battery technologies. This has aroused a vast level of interest in many research industries, but not much more advancement has been seen in the area of wireless sensor networks. This is limited by the fact that the size of the battery is a governing factor in producing a small sized network sensor device [2, 3, 4].

A network sensor is typically design diversified and is normally scalable and capable of supporting a vast level of applications. Such a sensor is capable of providing the essential support in medical, military and commercial applications such as emergency care, disaster response, vital sign sensor detection, battlefield awareness, localization, building monitoring, security monitoring, environmental monitoring, etc. There is a huge range of applications and it is desirable to have network sensors that are designed to accommodate this diversity. Mica-Z is a good example that is commonly utilized in medical and military and commercial applications [2, 3, 4].

B. SENSOR NETWORK ARCHITECTURE

Interconnection of sensors forms the network topology or architecture. The architecture of wireless sensor networks draws upon many sources and much research has been done in the context of self-organizing, mobile ad-hoc networks. The characteristics of self-organizing and low power operation govern the design of the network architecture to fit the different purposes, but they share the need for a decentralized and distributed form of organization. Sensor network architectures can be broadly separated into two categories: "layered architecture" and "clustered architecture" [2, 5, 6].

1. Layered Architecture

In a layered architecture, a network consists of a base station with multiple nodes, as depicted in Figure 1. Network sensors are organized in these "layers" based on their hop count to the base station. Sensors with the same hop count are grouped together in each layer. In this case communication between the farthest nodes to the base station is possible without having to use high power transmission. The main advantage of this is that it allows short distance communication between the nodes with high energy efficiency. It is capable of supporting hundreds of nodes in the network [2, 5]. A layered architecture was the architecture that all the experiments on which this thesis was based.

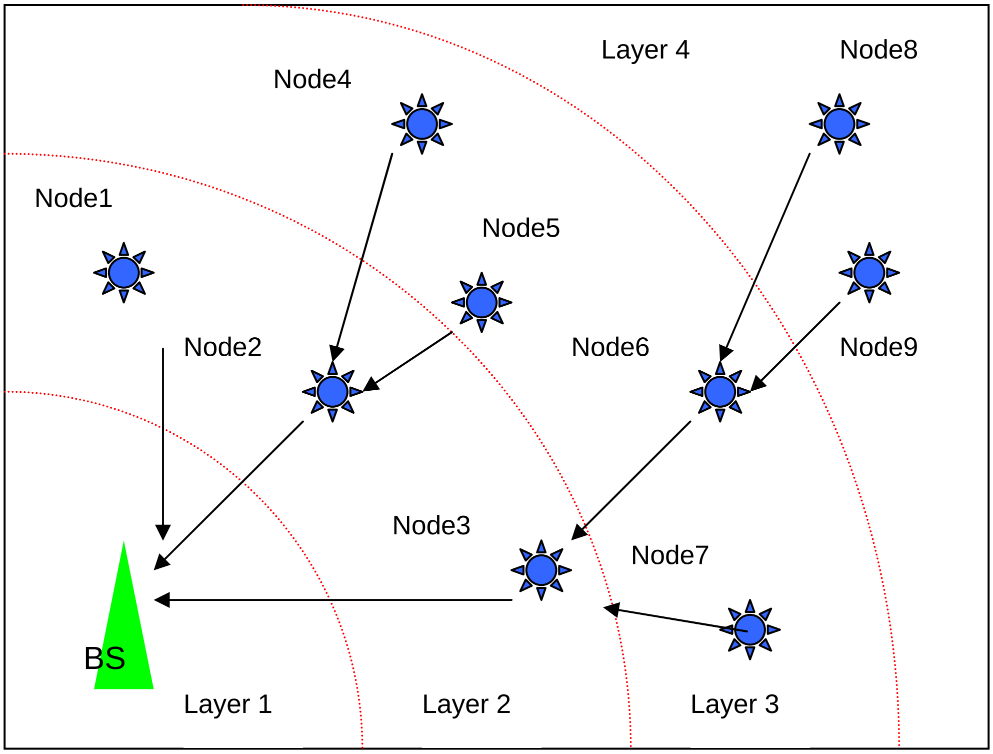

Figure 1. Layered Architecture (After Ref. [2, 5]).

2. Clustered Architecture

In a clustered sensor network architecture, the sensor node will communicate to the base station via the cluster head as depicted in Figure 2. The cluster head has two main roles: (1) intra-cluster coordination (i.e., coordinating among nodes in within its cluster), and (2) inter-cluster communication (i.e., communicating with other cluster heads and/or the base station). The main advantages of a clustering architecture are to increase scalability and reduce communication delay between the nodes [2, 6].

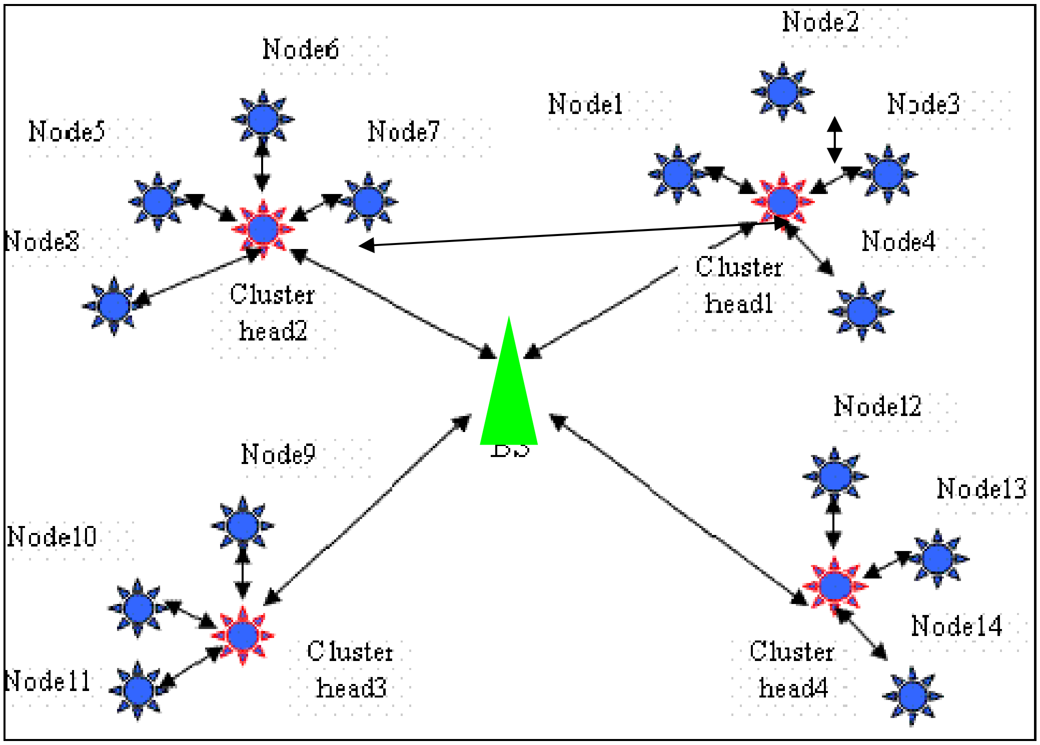

Figure 2. Clustered Architecture (After Ref. [2, 5]).

Each of the above architectures has it its own merit and suited applications and there is always a dilemma of having to strike a balance between energy efficiency, accuracy, and latency of the sensor network. There is no clear cut solution as to which is better, as the choice is dependent on the application and environment. Before one can make these choices, it is important to understand how the sensor network protocol works. This knowledge is always critical in the process of designing and building a simple, low cost and robust sensor network that matches different requirements.

In the following sections, the sensor network protocol will be discussed to provide a broad overview on how such protocol can be applied in a sensor network.

C. SENSOR NETWORK PROTOCOL

The operation of a wireless network sensor typically uses a layered protocol architecture when the wireless network sensor nodes exchange data.

The procedures involved can be quite complex and the implementation of the logic in a single module is rather difficult and non-systematic as a high degree of cooperation between the communication network sensor nodes is necessary for effective communication of a wireless sensor network. Basically, the work process is broken up into sub-modules where each sub-module can be treated and implemented separately from the other sub-modules. These sub-modules are arranged in a vertical stack where each layer performs a related subset of functions required to communicate with one another. The lower layer will typically perform more primitive functions to support the next higher layer operation. This layered approach has great benefits in keeping the entire protocol stack flexible, manageable and systematic. Figure 3 describes a typical layered protocol stack of a wireless sensor network. This is a four-layered protocol architecture which is organized in the following chronological order: physical layer, data Link layer, network layer and application layer. The physical layer covers the physical interface between wireless network sensor nodes for which bit streams are sent and received from one another. The data link layer is responsible for reliable transmission and reception of the data and provides some form of flow control. The network layer provides the transfer of information between end systems across the wireless sensor communication network. The application layer provides a mechanism to support distributed applications. In the subsequent discussion, this thesis will commence with the highest (application) layer and work towards the lowest (physical) layer [2, 3, 4].

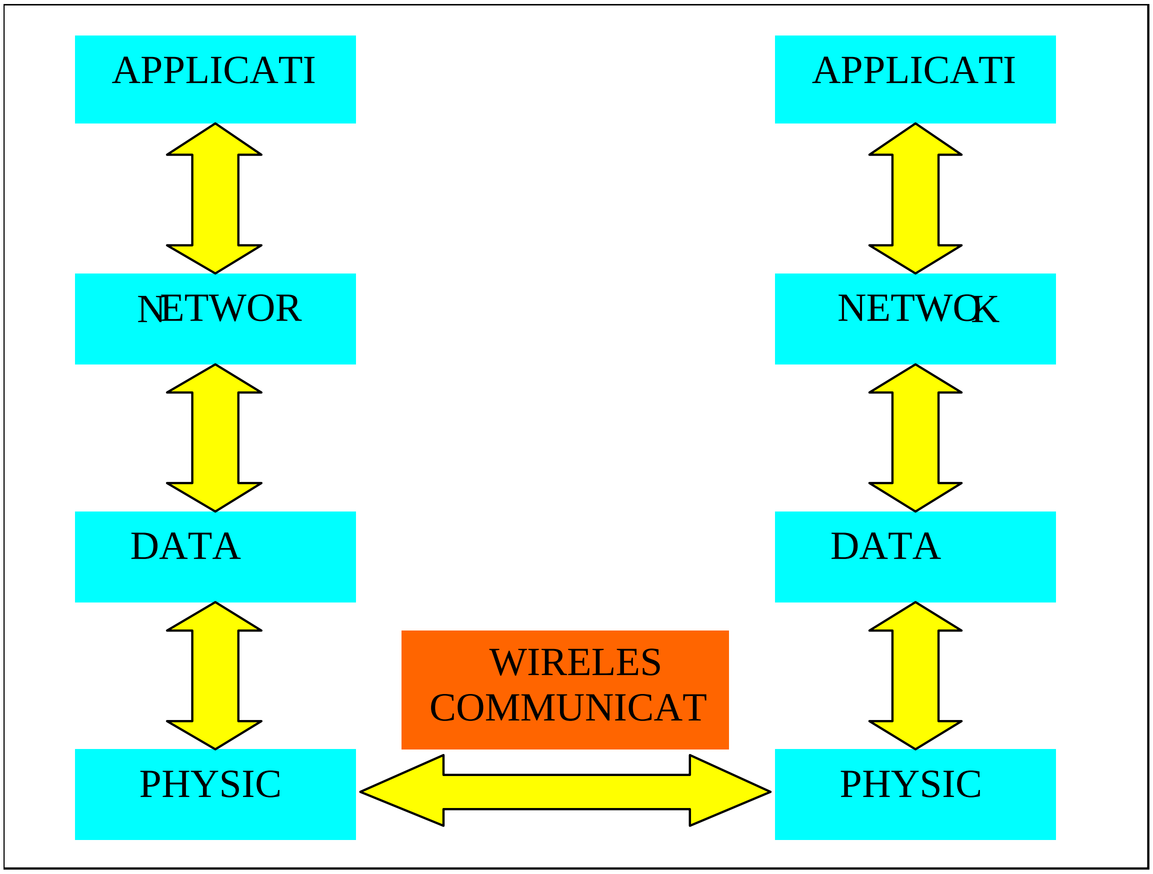

Figure 3. An example protocol stack of a wireless sensor network (After Ref. [4]).

1. Application Layer

The application layer contains the logic needed to support the various sensor applications. It provides a means for the network sensor application programs to access the wireless sensor network environment. In the context of a wireless sensor network, sensors define the application layer. They effectively convert the physical attributes into legitimate data that is suitable for wireless transmission. The physical quantity, which is typically analog, will be sampled, converted into a digital signal and formatted into packets before transmitting it to its designated network sensor node or a base station, depending on physical environment conditions [2, 3, 4].

2. Network Layer

The network layer provides for the transfer of information between end nodes across the communication mechanism of the wireless sensor network. This layer relieves the higher application layer of the need to know anything about the underlying data transmissions and routing mechanisms. In this layer, the source node will engage a link with the network and use different routing techniques to transmit the data effectively to the designated node or base station [3].

Most wireless sensor networks are multi-hop networks. That means that the source node will have to rely on the assistance of intermediate nodes to forward the intended information from the source node to the destination node. There are several different options of forwarding techniques that exist which govern the forwarding process. The simplest form of forwarding rule is flooding. During the flooding process, the packets are sent to all neighbors, and as long as the destination node is in the same network, the data is sure to be received by the destination node. The sensor is designed to forward the packet only once to avoid endless repetitive regeneration of the same packets. A time-out mechanism is usually embedded to avoid endless propagation of packets. This technique is simple to implement but encompasses the numerous duplications of packets which impact the efficiency of the network [3].

An alternative to the flooding technique is the gossiping technique. These techniques are at the two extreme ends of the design spectrum. The gossiping technique forwards the packets to any arbitrary node in hopes that the packets will eventually reach the destination node. This technique would minimize the duplication of packets but its inefficiency lies in the substantially longer delay of packets to reach the destination node [3].

A hybrid of the above two techniques is the controlled flooding technique, which complements the shortfalls of the flooding and gossiping techniques to optimize the performance of the sensor network. Using this technique, the source node can forward more than a single packet in a random fashion and the

receiving nodes will then forward the incoming packets to their other neighbors which will in turn repeat the same process until the packets reach the destination source [3].

The above techniques discussed are simple in design and implementation due to the fact that they ignore the network topologies. Their performance in terms of packets sent and received and delay is normally extremely poor. These shortcomings can be overcome by the implementation of routing table. The table typically encompasses the suitability of its neighbors for receiving the packets and the cost of routing the packets from the source node to the destination node. With such a technique, the packets can be transmitted effectively without having to compromise with the inefficiency of packet duplication and delay. The routing protocol will be able to use the information in the routing table to select the least expensive path effectively with minimum delay [3].

There are essentially two basic types of table routing protocols: table driven protocol and on-demand protocol. The only difference between them is that the on-demand protocol does not attempt to maintain routing tables at all times but only construct them when the network senses that a packet is required to be transmitted from a source node to a destination node [3].

There are several sophiscated routing techniques such as SPIN, GHT, SMCEN and X-mesh which could provide improvement in network efficiency. However, it is not the intent of this thesis to cover the full range of ad-hoc sensor networking in full detail, but rather to acknowledge the fact that the self-organization, low power, low overhead and changing topologies are important factors in deciding which routing protocols are to be used [2].

3. Data Link Layer

The Data link layer provides fair access to the physical layer and has the task of ensuring reliable transmission of the data from the source node to the destination node in the radio range. Its main tasks involve framing, error control, flow control and link management [3].

a. Framing

In the framing process, the transmitting node data link layer would accept the data packet and create a packet attaching a header, trailer, and checksum before transmitting the frame to the receiver. The receiver will use the checksum mechanisms to verify the integrity of the frame before accepting it. Acknowledgement may be sent back to the transmitting node upon the acceptance of the received frame. It is important to note that the choice of packet size is an important aspect of framing that will considerably affect the energy efficiency and throughput of the sensor network. An optimum packet size is essential in ensuring an energy efficient network, which is critical in low power sensor networking [3].

b. Error Control

Error control is an important task in the data link layer. The wireless medium can introduce noise into the transmitted waveforms and corrupt the information. It is a known fact that wireless transmission is more prone to error than wired media, where the physical effects of the environment such as reflection, diffraction, scattering, fast fading and inter-symbol interference make reliable transmission of the data packets extremely difficult. Some of the common correction mechanisms used to counter the effect of such losses includes redundancy and retransmission [3].

c. Flow Control

Flow control of the wireless sensor network uses a sliding window mechanism to control the flow of data packets between the source and destination nodes. It generally provides buffer windows (space) at both ends to store data waiting to be transmitted or processed. When the window is full it exercises flow control by forcing the transmitting node to slow down its transmission. This is normally not an issue in the area of the wireless sensor networks as the sensor nodes are normally low powered using low bit rate and the sliding window mechanism is sufficiently equipped to address the requirement in most wireless sensor networking applications [3].

d. Link Management

Link management of the wireless sensor network involves the discovery, setup, maintenance and tear-down of links among the neighboring nodes. Medium Access Control (MAC) is normally the protocol adopted by wireless sensor networks to carry out the support of the link management tasks. [3]

The MAC layer is the first sub-layer of the data link layer which offers its services to the network and other higher layers. Its fundamental task is to regulate the access of the sensor nodes to the shared wireless medium in the most efficient manner. Sensor network MAC protocols can be broadly categorized into three main classes, namely fixed assignment protocols, demand assignment protocols and random access protocols. Regardless of the class of MAC protocol that is selected for the wireless sensor network, the design of the MAC layer protocol has to strike a balance in the requirements of the sensor networks typically involving the parameters such as delay, throughput, fairness and energy efficiency [3].

4. Physical Layer

It is clear from the title of this thesis that the main area of focus is on the physical characteristics of the Mica-Z network sensor, and this primarily falls in the physical layer of the sensor network protocol. As such more time will be devoted to discussing the basic properties of this layer.

The Physical layer is a significant part of the protocol stack that would really shape the entire protocol stack of the sensor network. It covers the physical interface between network sensors/base station including transmitting channels and modulation scheme. The modulation scheme is not within the scope of this thesis. The main focus of discussion will be on the communication channel fundamentals [3].

a. Frequency Characteristics

Communication channels can be classified into wired and wireless, and in the context of wireless sensor network, it is the wireless channel which

this thesis focuses on. A wireless channel is an unguided medium in which the radio propagation is not bounded by any pre-defined environment. For a practical wireless RF-based system, the carrier frequency has to be very carefully selected to match the performance and environment of intent. It has a significant impact on the characteristics of the propagation. The use of these spectra is also rather restrictive due to the limited bandwidth available and the abundance of users fighting for the bandwidth. Figure 4 depicts the electromagnetic spectrum within which the wireless channel generally falls [3].

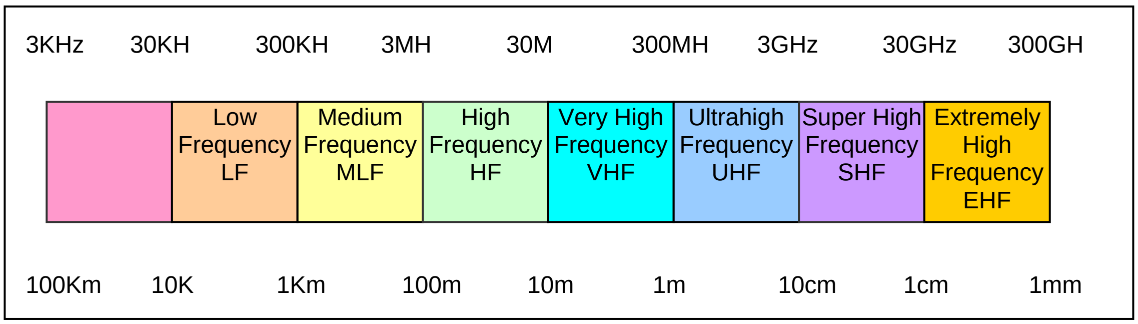

Figure 4. Electromagnetic Spectrum (After Ref. [3]).

In Figure 4 the top and bottom portions of the diagram depict the frequencies and wavelength respectively. The Mica family network sensor falls in the range of the ultrahigh frequency band (UHF) and its frequencies of operation include 315 MHz, 433 MHz, 868 MHz (Europe), 915 MHz (North America), and the 2.4 GHz. Crossbow Mica-Z network sensors are designed to operate in the frequency band of 2.4-2.48 GHz. Mica-Z radios can be tuned to the IEEE802.15.4 channels that are numbered from 11 (2.405 GHz) to 26 (2.480 GHz), each separated by 5 MHz. It is the intention of this thesis to explore the RF characteristics of this network sensor in the 2.480 GHz frequency band. This Industrial-Scientific-Medical (ISM) band provides implementation flexibility to the sensor network where there is an abundance of commercial RF devices available operating in this frequency band. In addition, the fee-free usage of this band also makes this an attractive option for many commercial users [3, 7].

The choice of operating frequency of the sensor network can have an adverse impact on its receiving power which in turn will directly affect the

communication range. Mica-Z uses high operating frequencies of 2.4-2.48 GHz which limit its communications range due to high path loss attenuation. However, high frequency operation is very often necessary if small sized antennas and low power consumption are required for the sake of easy deployment in a hostile environment. The only shortcoming in this public ISM band would be that the system would have to live with a high level of interference created by other users simply because there are limited usage constraints [3, 7].

b. Antenna Characteristics

Another critical area of interest in wireless transmission is antenna performance. The main parameters which define performance of an antenna are antenna gain (*G*) and beamwidth (*B*). The gain of the antenna is given as: [8]

$$G = \eta D$$

where

η : Radiation Efficiency

D : Antenna Directivity.

Antenna radiation efficiency (η) is defined by the ratio of radiated power to input power. The directivity (*D*) is defined as the ratio of radiation density in a particular angular direction to the radiation density of the same power radiation isotropically [8].

Beamwidth is the angular width of the main lobe of an antenna far field radiation pattern as measured from points on the main pattern lobe that are 3dB below the peak of the main loop. Beamwidth has an inverse relationship with directivity (*D*) given a fixed frequency [8].

This thesis will investigate the performance of the Mica-Z antenna based on these two parameters, as discussed in the previous three paragraphs, and also attempts to find a suitable way to improve the antenna performance. At the frequency band of 2.480 GHz, a typical Mica-Z antenna will be a few centimeters in length (i.e., a quarter wavelength of insulated wire). This is often

called a monopole antenna and its gain is ground plane dependent. With the size constraint imposed by the frequency band, the need for a small package and an omni-directional radiation pattern, the design of an effective antenna becomes a non-trivial exercise. Some alternative designs for the Mica-Z antenna are explored using the GNEC simulation software which will be discussed in greater detail in Chapter III [3, 8, 9].

c. Propagation Characteristics

In wireless sensor networking, the network sensors exchange information via the wireless medium though some form of signal waveform. This waveform propagates through the wireless medium and is constantly subjected to external effects such as reflection, diffraction, scattering, Doppler fading, multi-path, etc. The working mechanism of this phenomenon is clearly explained in references [3] and [10]. Basically, it is important to understand that the signal received at the receiving nodes is not a perfect replica of the transmitting waveform, but rather it is a superposition of multiple delayed waveforms with different attenuated power levels. It is for this reason that radio propagation is limited by its operating range and bandwidth [3, 10].

In order to have a greater appreciation of this thesis, it is important to understand the basic concept of path loss. First, this thesis will touch on the line-of-sight (LOS) free space propagation loss equation, also known as Friis Equation. This equation is given by [8].

$$P_{rx} = P_{tx} G_t G_r \left[\frac{\lambda}{4\pi r} \right]^2 = P_{tx} G_t G_r \left[\frac{c}{4\pi r f} \right]^2$$

where

P_{rx} : Receive Power

P_{tx} : Transmit Power

G_t : Transmit Antenna Gain

G_r : Receive Antenna Gain

λ : Operating Wavelength

r : Distance between Receive and Transmit Antenna

f : Operating Frequency

c : Speed of Light.

Therefore, the free space propagation loss in dB is given as: [8]

$$L_f\left[dB\right] = 10\log\frac{P_{rx}}{P_{tx}} = \left[10\log G_t + 10\log G_r - 20\log f - 20\log r + 147.56\right]dB.$$

This is the ideal case for line-of-sight (LOS) free space propagation. From the equation given above it is obvious that the operating frequency (f) and distance (r) are an inverse square function of the receive power (P_{rx}). In other words, one can observe a 6dB reduction in the receive power for every two-fold increase in the operating frequency or antenna distance. This again emphasizes the adverse effect of operating frequency and node distance on the sensor network system [8].

It is impossible to create a perfect LOS free space propagation model without any losses at all. However, it is possible to create a near free space model which is rather close to the free space model. One way to do this is to carry out the propagation in a controlled environment as such an RF anechoic chamber where all the surfaces within the chamber are padded with absorbers to minimize any losses caused by environmental effects (i.e., reflection, diffraction, fading, multi-path, etc.). This is often restrictive as it is expensive to build such a

chamber and work has to be carried out within the confined space of the chamber. Another way to do this is to create a direct LOS propagation path of network sensors to be within the 1st Fresnel zone. The formula used to calculate the Fresnel zone is as follows: [10]

$$F_m = \left[\frac{m \lambda d_t d_r}{d} \right]^{\frac{1}{2}}$$

where

F_m : Radius of m^th Fresnel Zone

m : Fresnel Index

λ : Operating Wavelength (m)

d_t : Distance from transmit antenna to mid point (m)

d_r : Distance from mid point to receive antenna (m)

d : Distance from transmit antenna to receive antenna (m).

In order to create a near free space model, it is essential to set up the network sensors in such a way that no obstacle is within 0.6m of F_1 (radius of first Fresnel zone). This concept is used in Chapter IV to measure the path exponent of near free space propagation [10].

In the real world of network sensor operations, the ideal case of LOS free space propagation is not always practical. The environment in which such sensor networks are required to operate varies with the applications and

requirements such as indoor monitoring, outdoor monitoring, urban communication, etc., where many different types of obstacles can stand in the way and block the LOS. This is known as non-LOS (NLOS) propagation. In such cases, a path loss exponent is normally added to the Friis equation to factor in for additional losses or gain other than the standard antenna gains. The modified equation is as follows: [8]

$$P_{rx} = P_{tx} G_t G_r \left[\frac{\lambda}{4\pi r_o} \right]^2 \left[\frac{r_o}{r} \right]^n = P_{tx} G_t G_r \left[\frac{c}{4\pi r_o f} \right]^2 \left[\frac{r_o}{r} \right]^n$$

where

n : Path Loss Exponent

r_o : Free space Propagation Distance.

The path loss exponent indicates that the rate of path loss increases with distance and provides an idea of how the environment affects the receive power. Due to the complexity of the environment, there is no one specific value of path loss exponent for any environment except for free space propagation (*n*=2). It is common that a range of values be used for each environment (i.e., indoor, open field, suburban, urban, etc.) and such data is normally achieved statistically or by means of simulation. Once the path loss is determined, users can use the parameter with some added contingency to design its network. In Chapter IV, some aspects of the path loss exponent of Mica-Z network sensor will be discussed [8].

This chapter provided an overview of the sensor network architecture and protocols that enable reliable design and operation of a wireless sensor network. This background information will help the reader to gain more appreciation for the measurement results which will be presented in the subsequent two chapters.

In Chapter III, the characteristics of the Mica-Z antenna will be discussed and simulated results of antenna modeling will be presented. This will be followed by the study of Mica-Z power characteristics in near free space, indoor and outdoor environments in Chapter IV.

III. RF CHARACTERISTICS OF MICA-Z ANTENNAS

This chapter begins with a discussion on the specifications of the Crossbow Technologies Mica-Z network sensor. It is important to understand the basic working principle of this network sensor before proceeding as it will give a source of comparison on those measurements which have been taken. The Mica-Z network sensor radio is a newly developed network sensor that is designed and built to be IEEE 802.15.4 compliant and ZigBee ready, and is compatible with the MIB510CA Mote interface board which will act as a network based station and programming interface for Mica-Z network sensor operation. As mentioned in the previous chapters, this wireless network sensor operates in the 2.40-2.48 GHz frequency range which falls in the ISM band. It uses a quarter wavelength monopole antenna for wireless transmission and reception as a result of the small size factor required. The mote module runs on TinyOS 1.1.7 or a higher version which is capable of reliable mesh networking. The Mica-Z network sensor is also compatible with the range of Mica family sensor boards such as MTS101/300/310/400/420/510CA to provide a variety of sensing modalities to match different applications. Data will be sent from the network sensor to the base station which is then passed on to the Surge and Mote View software applications to perform all database administration. More details of the Mica-Z network sensor can be found in its data sheet [11] and Crossbow's network sensor user guide [9, 12, 13, 14]. A picture of a Mica-Z network sensor is as shown in Figure 5.

Figure 5. Mica-Z Network Sensor (From Ref. [11]).

Two important aspects of the Crossbow Mica-Z antenna will be discussed here to characterize the performance of the antenna that is used in the sensor. They are Voltage Standing Wave Ratio (VSWR) and radiation pattern of the antenna. As part of the discussion of radiation pattern, the antenna gain and half-power beamwidth will be used to assess and compare the antenna radiation performance. An additional aspect to be discussed is the power attenuation based on antenna orientations before wrapping up the characterization of the Mica-Z antenna. After studying the characteristics of the Mica-Z antenna, a simulation tool, GNEC, will be used to assess some possibilities of antenna improvement that can be made to improve the overall performance of the Mica-Z network sensor.

A. VSWR MEASUREMENT

When there is mismatch of antenna impedance to the feed-line impedance, it gives rise to a second “traveling wave” which goes in the opposite direction from the incident wave. A measurement of this mismatch is known as the reflection coefficient, which is given as: [15]

$$\Gamma = \frac{Z_1 - Z_0}{Z_1 + Z_o}$$

where

Z_0 : Feed-line Impedance

Z_1 : Antenna Impedance.

As the two traveling waves pass each other in opposite directions, they set up an interference pattern called the “standing wave” and consequently give rise to the VSWR, which is given as follows [15]:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} .$$

The above equations are rather intuitive as a high reflection coefficient will result in high VSWR and vice versa. The best possible result of VSWR is 1:1 where there is no mismatch between the feed-line and antenna impedances (i.e., $\Gamma=0$) [15].

The VSWR measurement was taken for the Mica-Z antenna based on a characteristic input impedance of 50 ohms to verify the performance of this antenna in its operating frequency band of 2.40-2.48 GHz. An HP 8510C vector network analyzer was set up as shown in Figure 6 to take this measurement. The antenna consists of an MMCX right angle connector with 35 mm by 1 mm diameter wire attached to the center conductor. It was necessary to fabricate an adapter for the antenna MMCX connector. This adapter consisted of an SMA female connector, 9 cm of RG-173 cable and an MMCX jack. It is shown in Figure 7. The ground plane in this setup consists of the shielded portion of the antenna connector. This models the installation of the antenna on the mote which has a minimum ground plane.

Figure 6. VSWR Measurement Setup.

Figure 7. Mica-Z Antenna with Adapter.

In Figure 8, the VSWR of Mica-Z antenna was plotted over the range from 2 GHz to 3 GHz so as to provide a wider spectrum of comparison instead of just measuring the band of interest. The result showed that the minimum VSWR was recorded at the point of 2.30 GHz (VSWR=2) and not at the 2.40-2.48 GHz range where the sensor was designed to operate. The VSWR measurements taken between the frequency ranges of 2.4 GHz to 2.48 GHz were found to be between 3 and 5. This clearly showed that the antenna was not used at its optimum operating frequency of 2.30 GHz, and that perhaps some improvements can be made in this aspect of antenna operation.

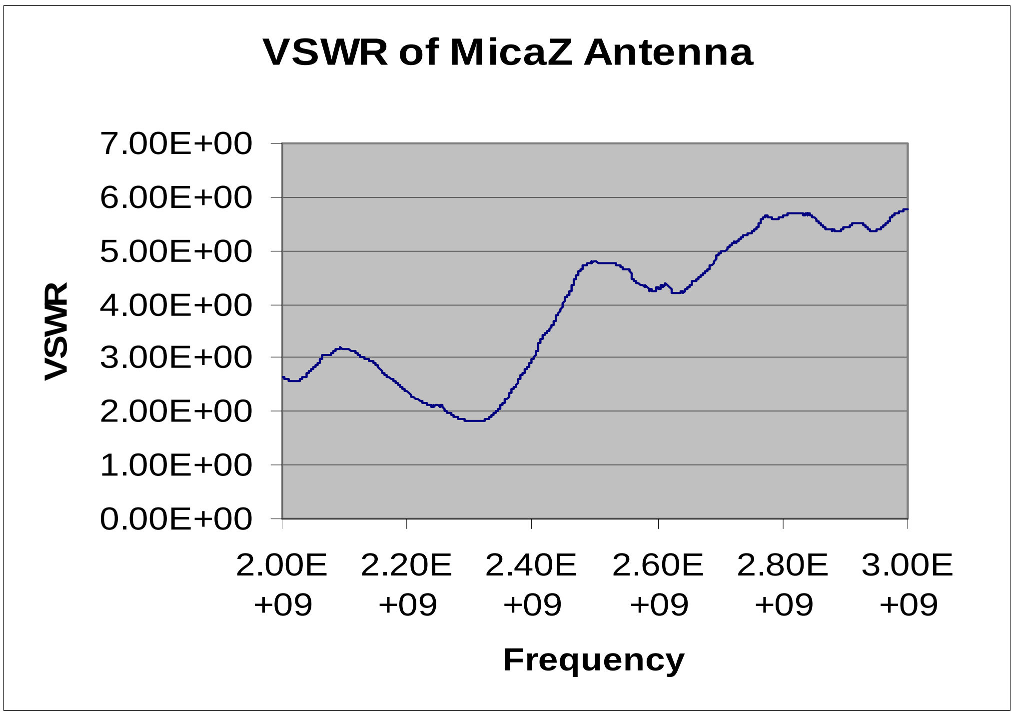

Figure 8. VSWR of Mica-Z Antenna with 50 Ohms Input Impedance.

The adapter that was required to connect the antenna to the network analyzer is clearly not identical to the antenna feed point on the mote. This is due to the limited information about the RF design of the mote. As a result, this measurement may not accurately represent the VSWR of the antenna as used with the mote but it gives a qualitative estimation of the operating frequency band.

For purposes of comparison, similar measurements were taken using a HP 8510C vector network analyzer on a Mica-2 antenna in the frequency range of 2 GHz to 3 GHz. The VSWR measurements of the two sensor antenna as shown in figure 9 were plotted in Figure 10.

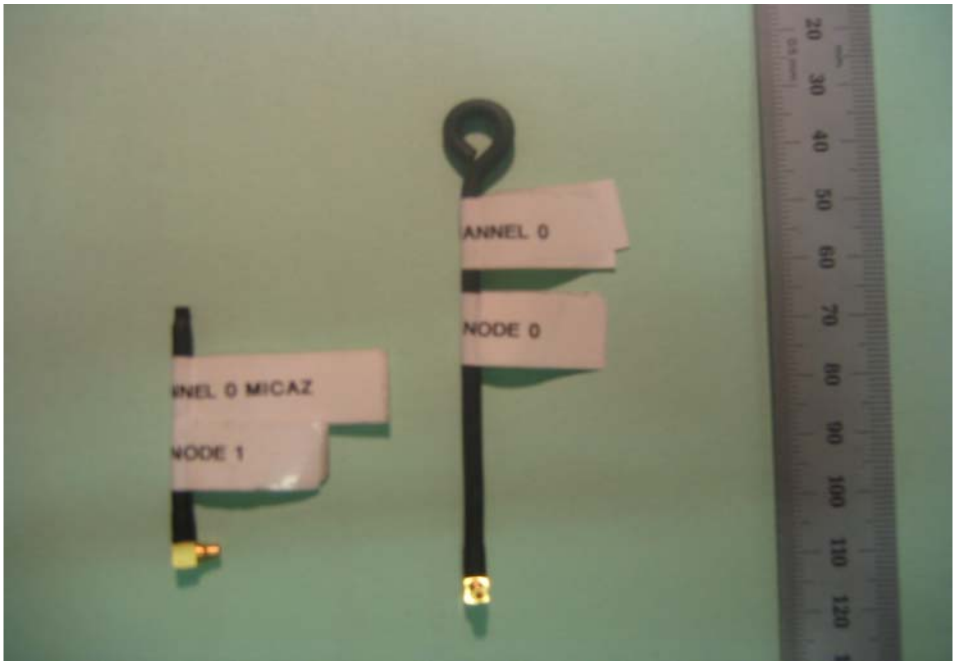

Figure 9. Mica-Z and Mica-2 Antennas.

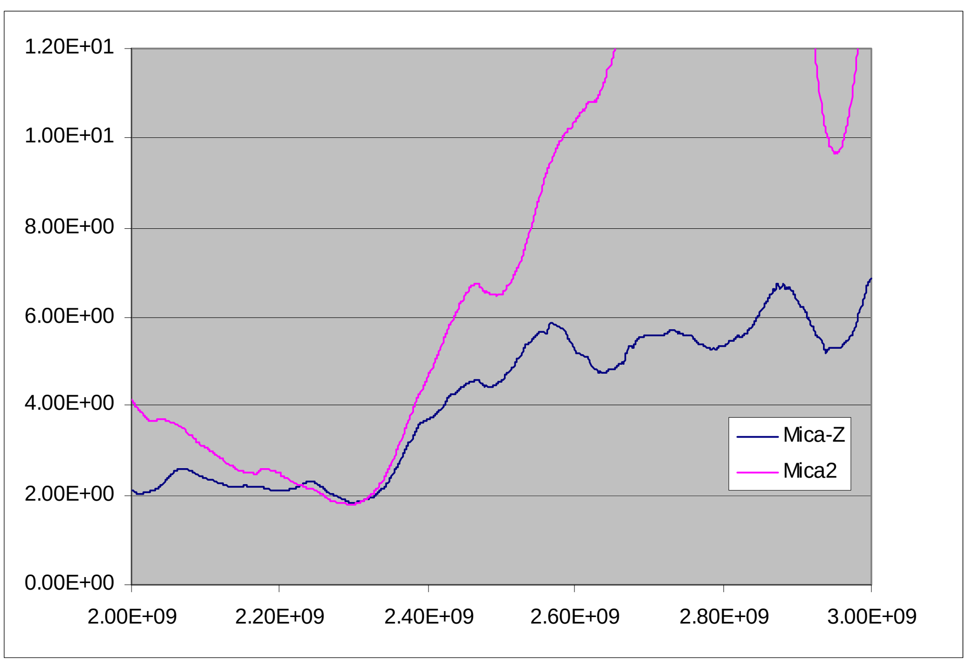

Figure 10. VSWR: Mica-Z vs. Mica-2 Antennas with 50 ohms input impedance.

Based on the results shown, the Mica-Z antenna would seem a better choice of antenna to operate in this frequency band. This is not surprising as the length of the Mica-Z antenna is designed to operate in this frequency band while the Mica-2 antenna is designed for operating frequencies of 433 MHz, 833 MHz and 900 MHz.

VSWR is important but not sufficient to determine the best choice of antenna. In the next section, the radiation pattern of the Mica-Z antenna, more specifically, the gain and half-power beamwidth of the antenna will be discussed to provide a more complete analysis of the antenna characteristics.

B. MICA-Z ANTENNA RADIATION PATTERN

Wireless network sensors employ antennas to transmit and receive information signals. The antennas are specifically tailored to have radiation patterns which meet their system requirements. Such is the case of the Mica-Z antenna. Each antenna will have its shaped beam and gain to optimize signal transmission and reception over its desired coverage area of operation [16].

The measurement of antenna radiation pattern is an important step in the design of an antenna to match its application. It is the one true way to determine antenna parameters such as gain, half-power beamwidth, and sidelobe level. As part of this thesis, a measurement of the Mica-Z antenna radiation pattern was carried out in an anechoic chamber. The Naval Postgraduate School (NPS) anechoic chamber, located in Spanagel Hall (Room 604), was used to carry out these measurements. The detail of the chamber characteristics can be found in [16]. A schematic diagram of the chamber equipment is shown in Figure 11.

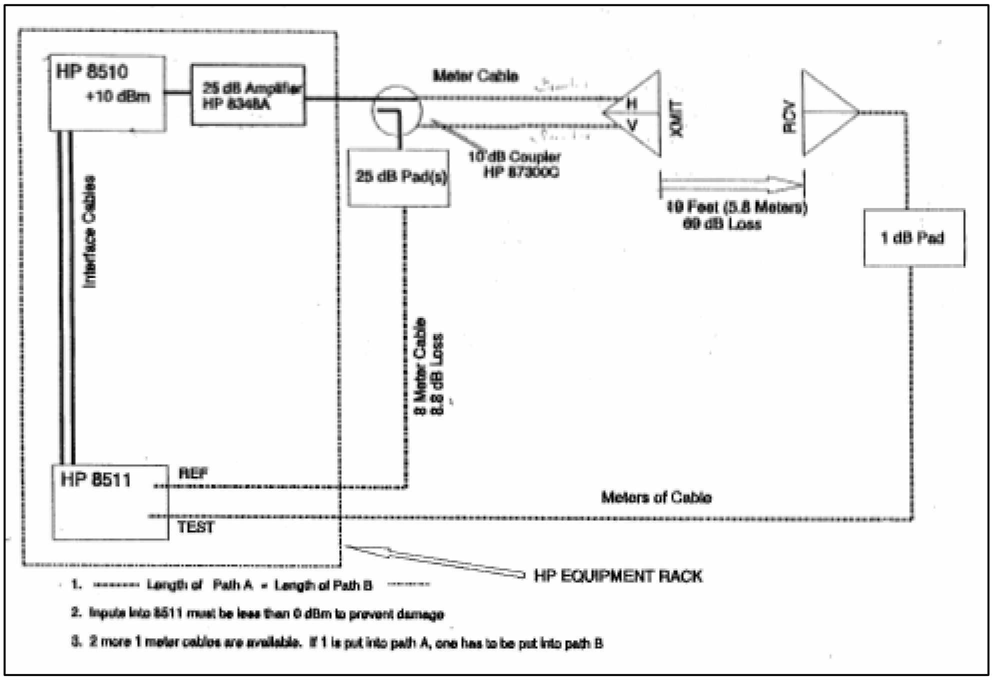

Figure 11. Schematic Diagram of NPS Anechoic Chamber.

This anechoic chamber is not completely lossless; however, it is sufficient in the context of this thesis to obtain a near free space antenna pattern. The anechoic chamber is an enclosed environment that is equipped with necessary absorbent materials on all the sides of the chamber walls, ceiling and floors. The data was captured using a horn antenna as the transmitting antenna and the Mica-Z antenna as the receiving antenna. Figure 12 shows a picture of the NPS anechoic chamber that was used in the Mica-Z antenna radiation measurement [16].

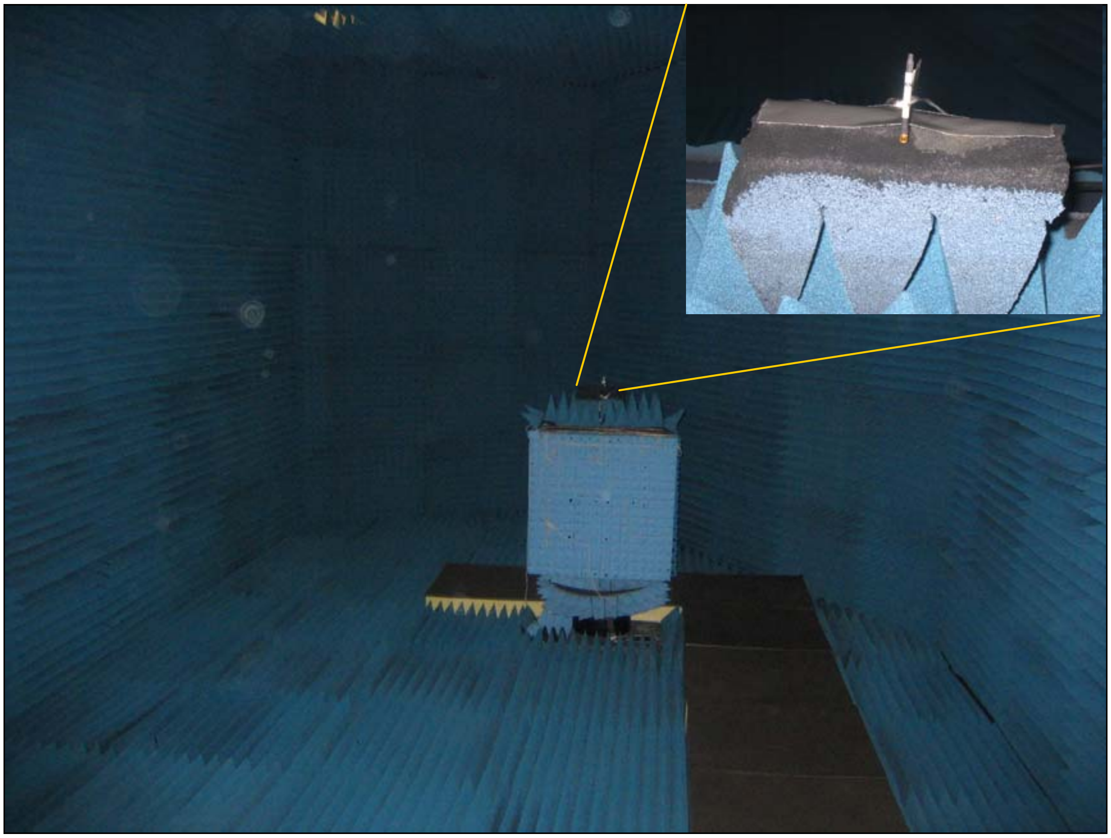

Figure 12. Anechoic Chamber.

In this measurement, there was no specific ground plane used and the only limited grounding was provided by the outer conductor of the connector attached at the bottom of the receive antenna. The receive antenna (Mica-Z) was placed vertically at the center of rotation table and rotated 360 degrees while receiving the transmitted power from the horn antenna. This was to establish the H-plane radiation pattern of the Mica-Z antenna. The same procedure was repeated with the receive antenna placed horizontally to establish the E-plane radiation pattern of the antenna. Combining these results will yield the Mica-Z antenna radiation pattern as shown in Figure 13. The 3-dimensional pattern was plotted using the LVDAM software. The antenna is at the origin of the axes and is oriented vertically in this figure. [16]

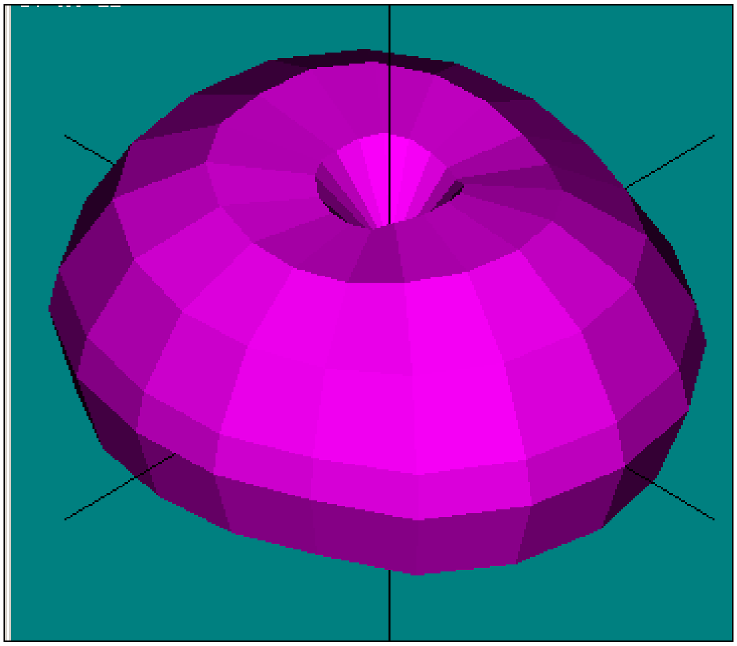

Figure 13. Mica-Z Radiation Pattern.

It was observed from this measurement that the radiation pattern of the Mica-Z antenna is omni-directional in the plane perpendicular to the axis of the monopole. The gain was close to 2.94dB and a half-power beamwidth of approximately 66 degrees (+/-33 degrees). The gain was calculated from the system loss {S21} measured in the anechoic chamber using the Friis equation as shown in Chapter II and the calculation is as follows:

$$SystemLoss = \frac{P_{rx}}{P_{tx}} = G_t G_r \left[\frac{c}{4\pi rf}\right]^2$$

$$295.12 \times 10^{-6} W = (50) G_r \left[\frac{3\times10^8 \, m/s}{4\pi(5.75m)\times2.40\times10^9 \, Hz}\right]^2$$

$$G_r = 1.97 = 2.94dB$$

Such information is necessary and crucial to users when designing a wireless sensor network. Users will need all this information to ensure that their

placement of the network sensors does not fall outside the effective half-power beamwidth and range of the system. As an illustration, if the network sensor is deployed in an undulating terrain, the performance will be greatly affected by the fact that such conditions may cause the network sensor to fall outside the effective beamwidth of the antenna resulting in ineffective or failed communication. The situation will be much better if such network sensors are deployed on a level terrain.

Another factor that could affect the deployment decision of a sensor network is the varying antenna position during deployment. This will be discussed in greater detail in the following section.

C. LOSS DUE TO ANTENNA ORIENTATION

In general, the signal power received by the receiving antenna is dependent on the orientation of the receive antenna with respect to the transmit antenna and more loss is likely to be experienced if there is polarization mismatch. This represents another source of error which may affect the entire sensor network design, especially in the case of random node deployment. Based on the Mica-Z antenna pattern, it was easy to tell that the worst case scenarios (maximum losses) occurred when the transmit and receive antenna are placed perpendicular to each other, as in the case of 2 to 5 in Figure 10; and the best case scenarios (minimum losses) coincide with the situation when the transmit and receive antenna are parallel to each other, as in the case of 1 and 6 in Figure 14. The six cases of orientation chosen will cover all the best and worst cases of the loss possible in all line-of-sight operations [17].

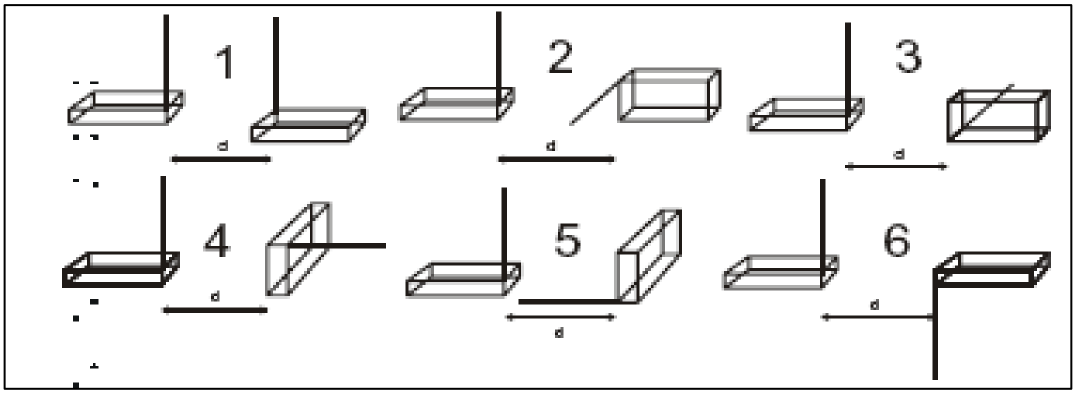

Figure 14. Six Mica-Z Antenna Configurations (From Ref. [17]).

Again, these measurements were carried out in the same anechoic chamber mentioned in the earlier section. The original transmitting horn antenna was replaced with the Mica-Z antenna and the receive antenna uses the same Mica-Z antenna. The receive and transmit antennas were consistently placed 20 feet apart for all the six orientation measurements so as to set a fair basis of comparison. The receive antenna was connected directly to the input of the spectrum analyzer where the received power readings were directly taken, as shown in Figure 15.

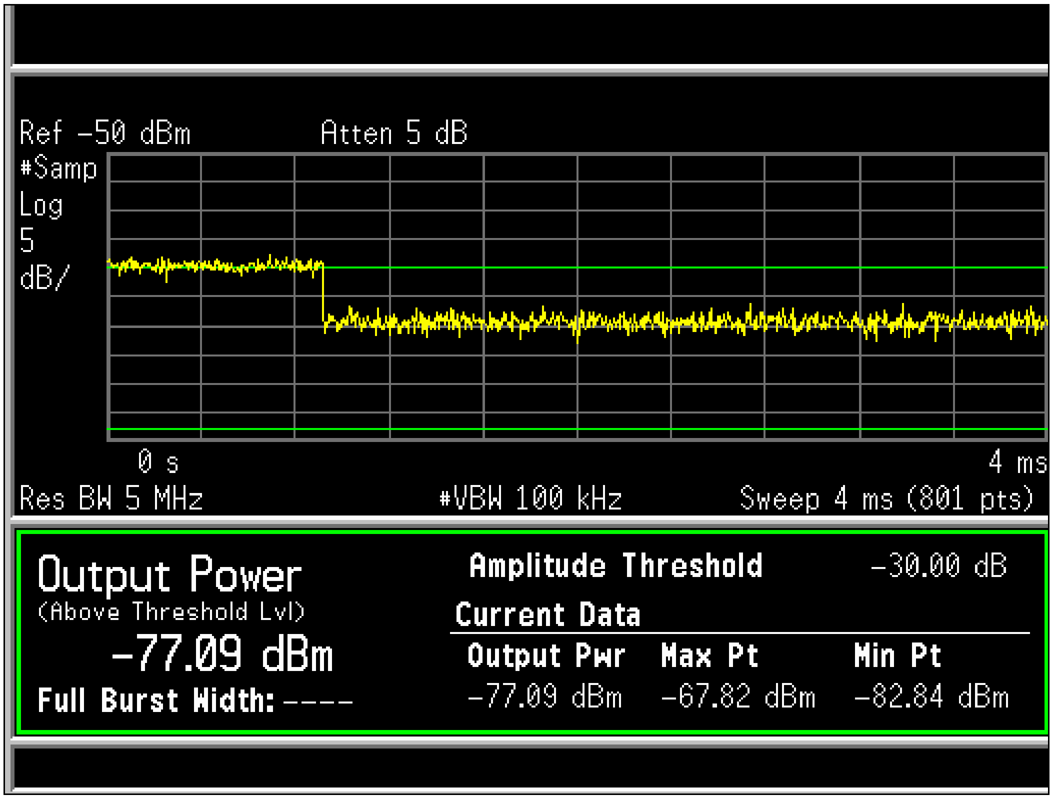

Figure 15. An example of Received Power Reading from an Agilent E4405B Spectrum Analyzer.

After the setup and measurement of receive power for all six orientations mentioned in Figure 14, comparisons were made between the measurements taken and the results are as shown in Table 1. The results shown were less than the ideal free space expected power and this was likely due to reflections from the chamber's walls and the measurement equipment. As predicted, the results showed that drastic variation occurred over the orientation of 2 to 5 versus the orientation of 1 and 6. The maximum variation recorded was approximately 10 dB, which is substantial as far as a WSN is concerned. The power loss would have direct impact on the effective range of the WSNs and would therefore affect its operational capability. [17]

	Antenna Orientation					
	1	2	3	4	5	6
Min Power (dBm)	-61.23	-65.73	-66.28	-66.48	-67.02	-62.39
Max Power (dBm)	-57.16	-62.67	-63.04	-63.11	-63.49	-59.57

Table 1. Effect of Antenna Orientation.

In all network sensor deployments, it is critical that such power loss is taken into consideration in the design of a sensor network. This is especially true in the case of a random deployment where the user cannot enforce a specific orientation of sensor position to ensure optimum communication. It is also essential to note that the 10dB power deviation observed earlier was specific to this chamber experiment and may not apply for more general situation. More work may be needed to quantify the loss.

Three important aspects of the Mica-Z antenna were highlighted and their impacts on sensor network design were also discussed. It is impossible to achieve a good design of a sensor network system without the knowledge of all these parameters. Hopefully, the results collected above will provide users a good overview of the Mica-Z antenna characteristics and help them in the design of sensor network system using the Mica-Z network sensors.

D. GRAPHICAL NUMERICAL ELECTROMAGNETIC CODE (GNEC) MODELING

The preceding sections have highlighted the importance of understanding the characteristics of the network sensor antenna before designing any sensor network system. However, this is using available resources to satisfy design requirements which may not always be feasible. In cases where only a limited numbers of sensors can be deployed, it will be necessary to re-examine the current Mica antenna design and seek means to improve the antenna radiation pattern, gain and half-power beamwidth to match the varying application and environmental requirements.

It is this motivation that drove the use of the antenna modeling program to find a mean to enhance the Mica-Z antenna design. In this thesis, the GNEC

antenna modeling program was selected to do this task. This software is capable of automating and displaying the antenna modeling predictions.

Some Mica-Z antenna design enhancements were considered and modeled using the GNEC program, including end-loop, top-loaded and turnstile antenna models. All of these simulations used an infinite ground plane. The current Mica-Z monopole antenna was also modeled so as to serve as a means of comparison. It is essential to understand that these selections are by no means exhaustive, but they do provide an idea of how antenna design can affect the performance of a sensor network. It is also important to note that the models were selected with a small form factor in mind, and some thought was invested to ensure that each model is not oversized to such an extent that it becomes impractical for deployment. The results are presented and discussed in the next few sections.

1. Monopole Antenna (Model 1)

As expected, the simulated radiation pattern obtained from the monopole antenna is very similar to the actual radiation pattern of the Mica-Z, which was shown in Figure 13. This is to be expected as the modeled antenna is constructed using the actual Mica-Z antenna as the baseline. The simulated radiation pattern is shown in Figure 16.

A maximum antenna gain of 4.43 dB and half-power beamwidth of 43 degrees was recorded in this omni-directional radiation pattern using this simulation model, and these values would be taken as the basis of comparison for the subsequent antenna modeling designs.

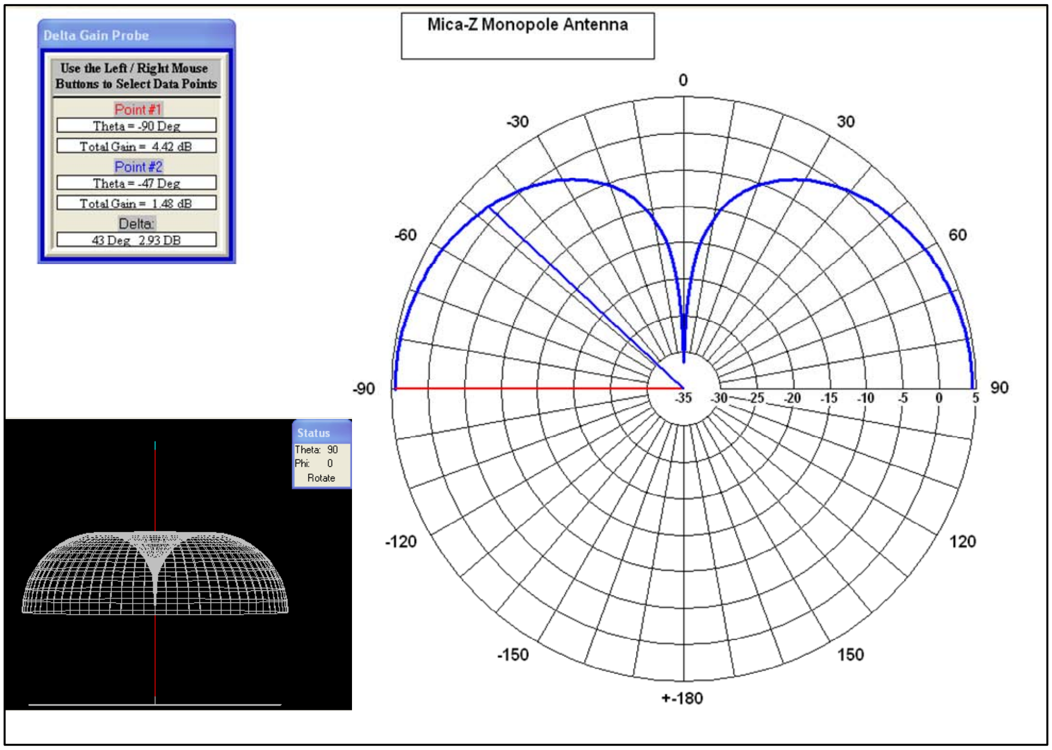

Figure 16. Radiation pattern of Monopole Antenna.

2. End–Loop Monopole Antenna (Model 2)

This model is based on the Mica-2 antenna design where the top of the antenna is ended with a loop, as shown in Figure 17. This resulted in the same omni-directional radiation pattern except that the entire radiation pattern is offset slightly from the center of the antenna, which is good when more gain on one side is required relative to the other. Some deviations in the antenna gain and half-power beamwidth were also observed. An antenna gain of 6.1 dB and a half-power beamwidth of 39 degrees were recorded. This model provides a higher antenna gain with slightly lower half-power beamwidth. Based on the result obtained, this model is deduced to be more suitable for even terrain deployment, where extended range is required and the half-power beamwidth requirement is less demanding.

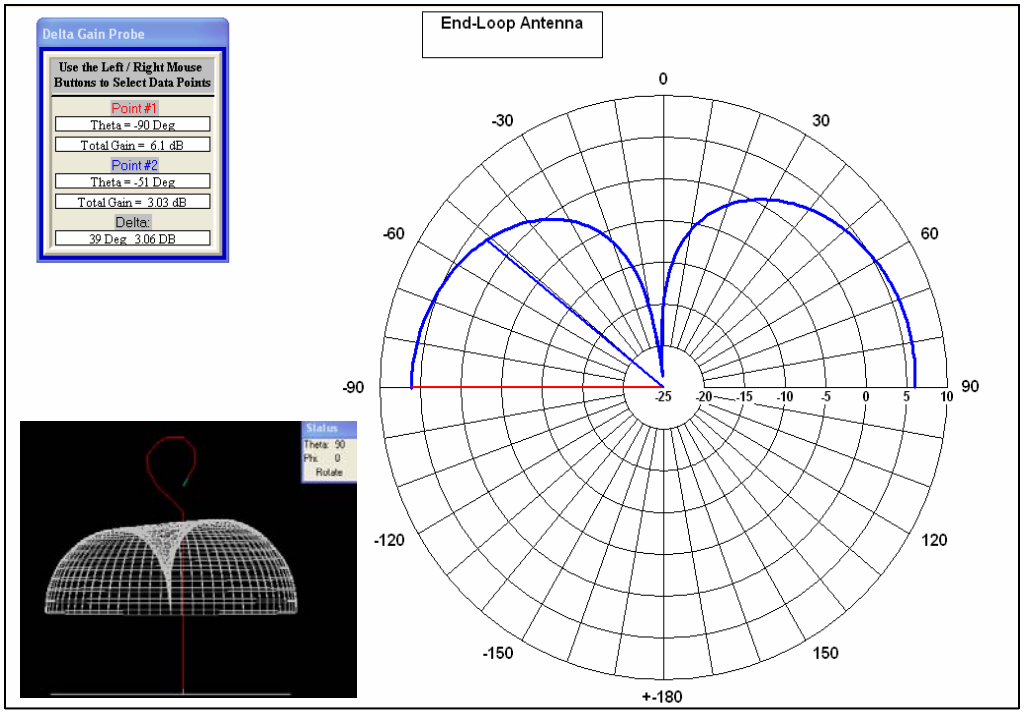

Figure 17. Radiation Pattern of End-Loop Antenna.

3. Top-Loaded Monopole Antenna (Model 3)

Another model that will be discussed is the top-loaded monopole antenna. The top of the monopole is loaded with a pair of wires in cross configuration as shown in Figure 18. Each of these wires is a quarter wavelength long, intersecting at the midpoint of each other. The radiation pattern is again similar to that of model 1, which is omni-directional, but there is substantially more antenna gain using this model than model 1 without much compromise in the half-power beamwidth. The maximum gain is recorded at 5.11 dB and the half-power beamwidth is 56 degrees. This model may be a good potential candidate for air dropped sensor network, where a monopole antenna top-loaded with propellers and properly located on an aerodynamic shape package causing the package to land on ground with high probability of landing in the desired orientation. All these can be done without any compromise in the antenna performance.

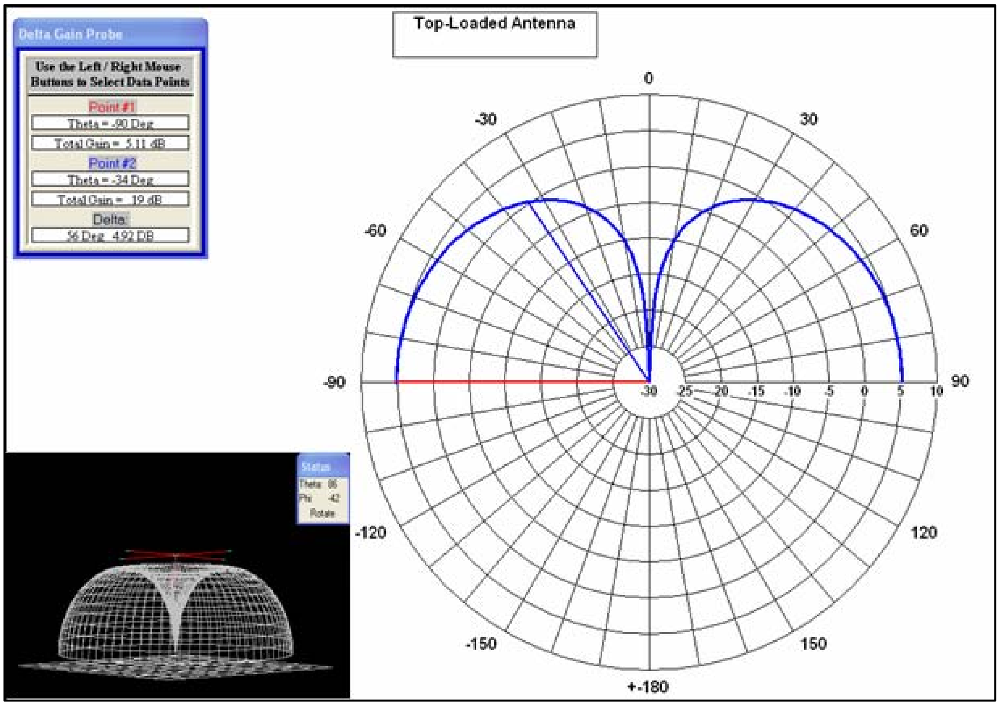

Figure 18. Radiation Pattern of Top-Loaded Monopole Antenna.

4. Turnstile Monopole Antenna (Model 4)

This is the last model that will be discussed in this section. This antenna is based on a classic turnstile configuration for circular polarization. Two dipoles are placed on the same plane but rotated at 90 degrees from each other and all connected with a quarter wavelength of transmission line. The lower element is driven at the center. These dipoles are a quarter wavelength above a ground plane [18]. The plot in Figure 19 shows the phi-plane pattern for this antenna. This model has the worst performance in terms of antenna gain, but it has the best performance in terms of half-power beamwidth as compared to the last three models discussed. The antenna gain is only 1.02 dB and the half-power beamwidth is a whopping 102 degrees. This is due to cross polarization of this model that makes it less sensitive to antenna orientation. This model can be used if maximum beamwidth is required.

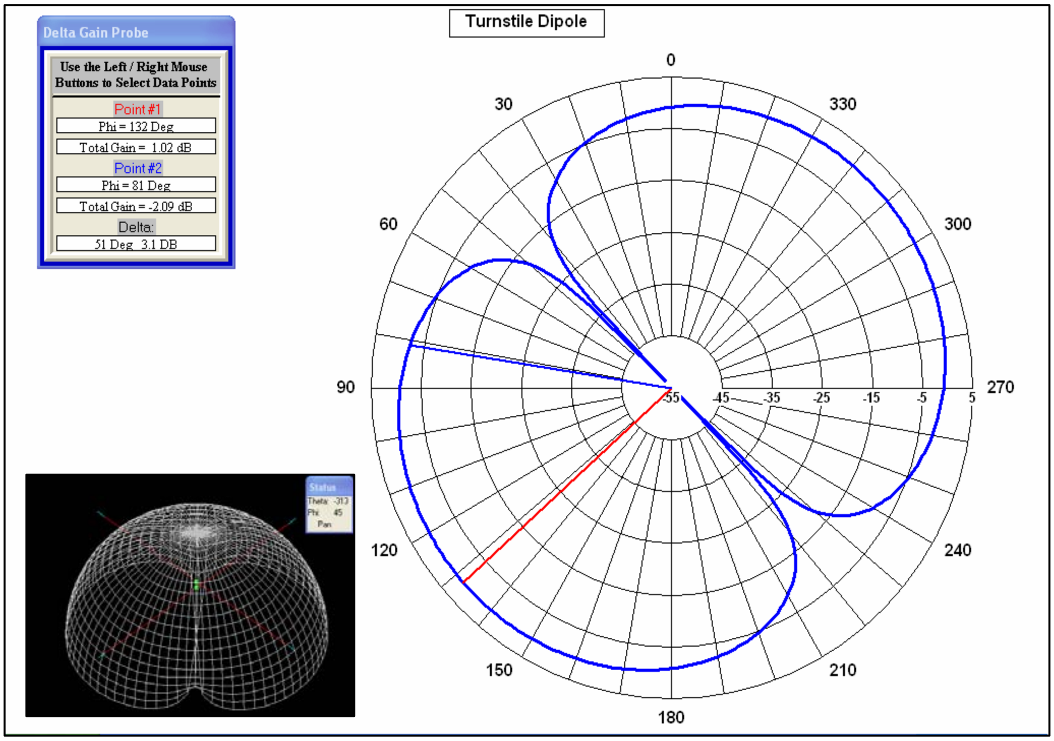

Figure 19. Radiation Pattern of Turnstile Antenna.

Based on the above discussion, it becomes apparent that antenna design will affect performance in a sensor network design. It also shows that a sensor network can change the design of an antenna to match the deployment constraints. There are too many variations in the application of a sensor network and therefore there is no one antenna that is good for all applications. As such, it is the intent of this thesis to highlight some of these possible improvements which may be useful for some special applications. Other aspects of antenna design may also be explored, such as a directional antenna or the use of a reflector to increase the gain of the antenna. However, this will have a great impact on the feasibility of deployment, especially for cases where the users cannot guarantee that the network sensors will be deployed within the effective beamwidth of the directional antenna.

In the next chapter, different aspects of the Mica-Z network sensor will be discussed. They encompass the relationship between the battery voltages with the break and re-associate distance of the Mica-Z network sensors, followed by RF power measurements in the near free space, indoor and outdoor environments.

IV. RF POWER CHARACTERISTICS OF THE MICA-Z NETWORK SENSOR

The propagation and attenuation profile for received signal power is a very complex function of the relative positions of sensors in an uncontrolled environment. It is important not only for system design and performance, but also for understanding the potential impact that it may have on other users or devices. In order to understand the power and propagation characteristics of a Mica-Z sensor network, studies were conducted to establish the path loss exponents in near free space, indoor and outdoor environments. In addition, measurements illustrating the relationship between the battery power and break and re-associate distances of the sensor network were also discussed in this chapter to provide a more complete perspectives of the Mica-z RF power behavior [19].

A. PATH LOSS EXPONENTS

The path loss exponent is a critical parameter that is commonly used to characterize the radio propagation channel: it indicates the rate at which the path loss increases with distance. The value of the path loss exponent is dependent on the propagation environment and it can potentially vary widely from one environment to another. It gives the user an indication of how the network sensor will behave in a specific environment, which is critical in any network system design. The purpose of this section is to discuss the power measurement results taken in the near free space, indoor and the outdoor environments, and derive the path loss exponent to characterize the propagation characteristics of the Mica-Z network sensor [19, 20].

1. Near Free Space Propagation

As illustrated in Chapter II, power received by each network sensor can be computed using the Friis equation. To ensure that measurements are correctly taken, it is necessary to set up a near free space environment where environmental attenuation is minimized. As mentioned earlier, the most ideal location would have been to take the measurement inside the anechoic chamber

where the attenuation is minimized. However, this was not possible due to the limited size of the chamber. As a result, alternate locations were surveyed and the Spanagel Hall roof top passage was found to be very suitable to carry out the measurements. The location was found to have a direct clear passage that stretches beyond 300 ft and has sufficient width of approximately 20 ft to ensure that all obstacles, such as walls, pillars etc, are not within the Fresnel zone of the LOS propagation. The transmit sensor, receive antenna and base station are placed on 2.5 ft high platforms. Using the Fresnel equation as specified in Chapter II, the first Fresnel radius (F_1) is computed to be approximately 7 ft based on the operating frequency of 2.4 GHz and an operating range of 500 ft. Clearly, the selected site has sufficient lateral clearance to ensure all obstacles are outside 0.6 x F_1 = 4.2 ft as shown in Figure 20, but the floor was within the Fresnel zone. In the layout as shown in Figure 20, the yellow indicates the location of the transmit sensor, the blue circle indicates the location of the base station and the red triangle indicates the location of the receiving antenna and the spectrum analyzer.

It should be noted that it is impossible to eliminate the multi-path interference completely with the above setup, especially when the grazing angles are relatively small. However, this limitation was accepted in the measurement as a result of unavailability of a more suitable location with low human traffic.

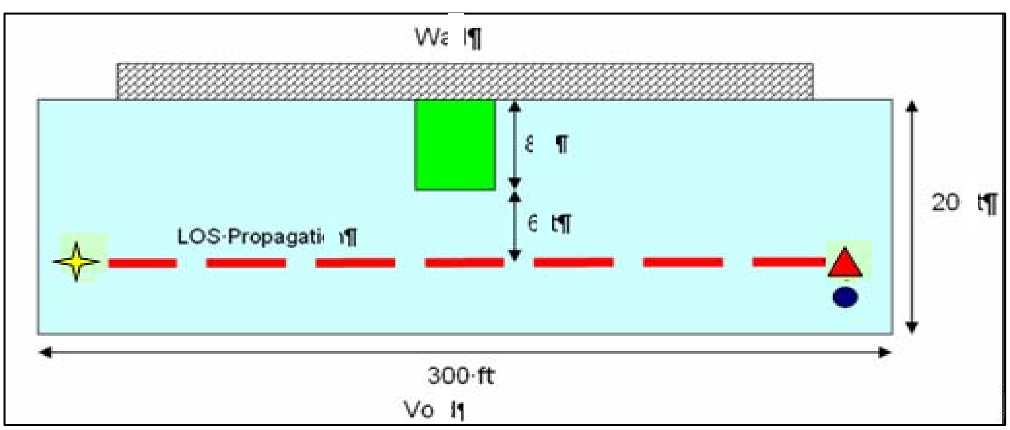

Figure 20. Layout of Spanagel Roof Top Passage.

Based on the above analysis, one could simulate a near free space propagation model and measure the receive power at the receive antenna. The received power measurements were taken using the setup as shown in Figure 21.

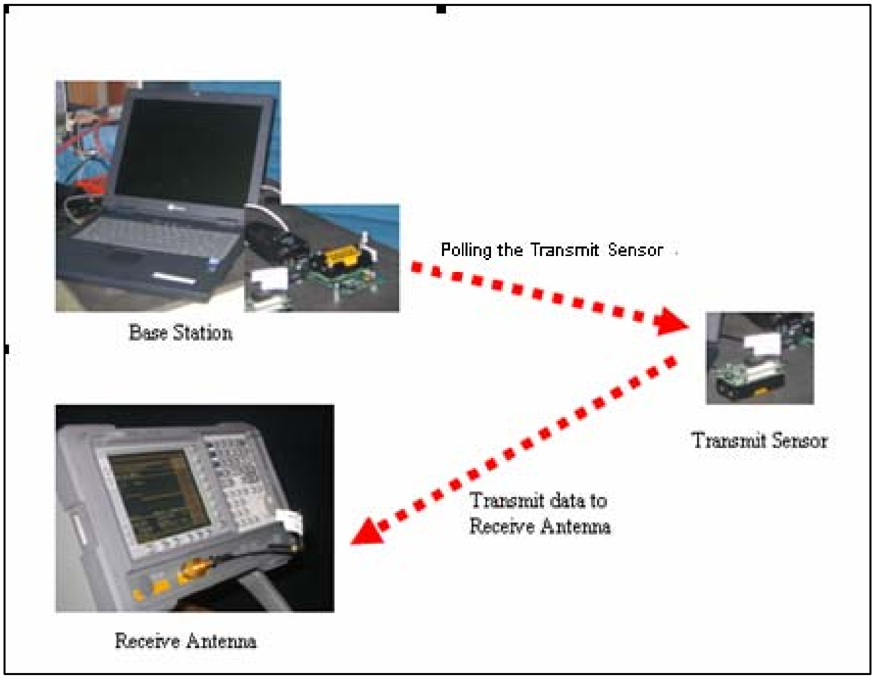

Figure 21. Measurement of Receive Power of the Mica-Z Network Sensor.

The received power measurements were taken at incremental steps of 10 ft separation between the transmit sensor and receive antenna until a break point was experienced. The baseline for the measurement was as follows:

- Transmitting power set at 0 dBm.
- Constant 3 volt battery supply to the network sensor.
- Operating frequency of 2.40 GHz.

After taking the considerations of all the antenna gains and other attenuation factors, the received power of the near free space propagation was recorded and plotted as shown in Figure 22. The theoretical received power was also plotted for comparison. From Figure 22, it was clear that the actual power

loss pattern matched the theoretical power pattern with consistent power deviation between the two curves. The lower measured power was likely due to VSWR loss.

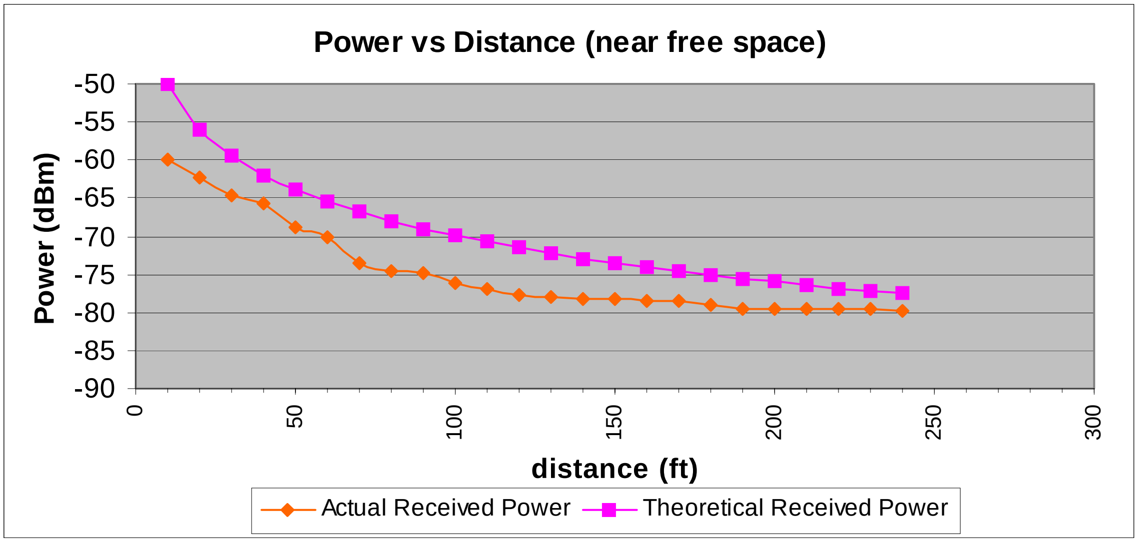

Figure 22. Path Loss of Near Free Space Propagation.

2. Indoor Propagation

The propagation characteristics of indoor propagation are substantially different from near free space and outdoor propagation. This is due largely to the wide variability of the indoor environment. For example, the indoor setup of office equipment and partitions is different from the outdoor setup of trees and plants. Typically, in the indoor environment, more attenuation will be experienced [19].

The measurement setup depicted in Figure 21 was used to measure the path loss of the indoor environment based on the layout depicted in Figure 23. The transmit sensor, receive antenna and the base station were placed on platforms that were 5ft height above the ground. Measurements were taken at incremental steps of 10 ft, and at every increment of 10 ft, measurements were taken at -45, 0 and 45 degrees. In Figure 23, the yellow star indicates the location of the transmit sensor, the blue circle indicates the location of the base station and the red triangle indicates the location of the receive antenna and spectrum analyzer. Figure 24 demonstrates the attenuation behavior of each

case of propagation. From the overall result, it was observed that heavy attenuation was experienced for indoor environment.

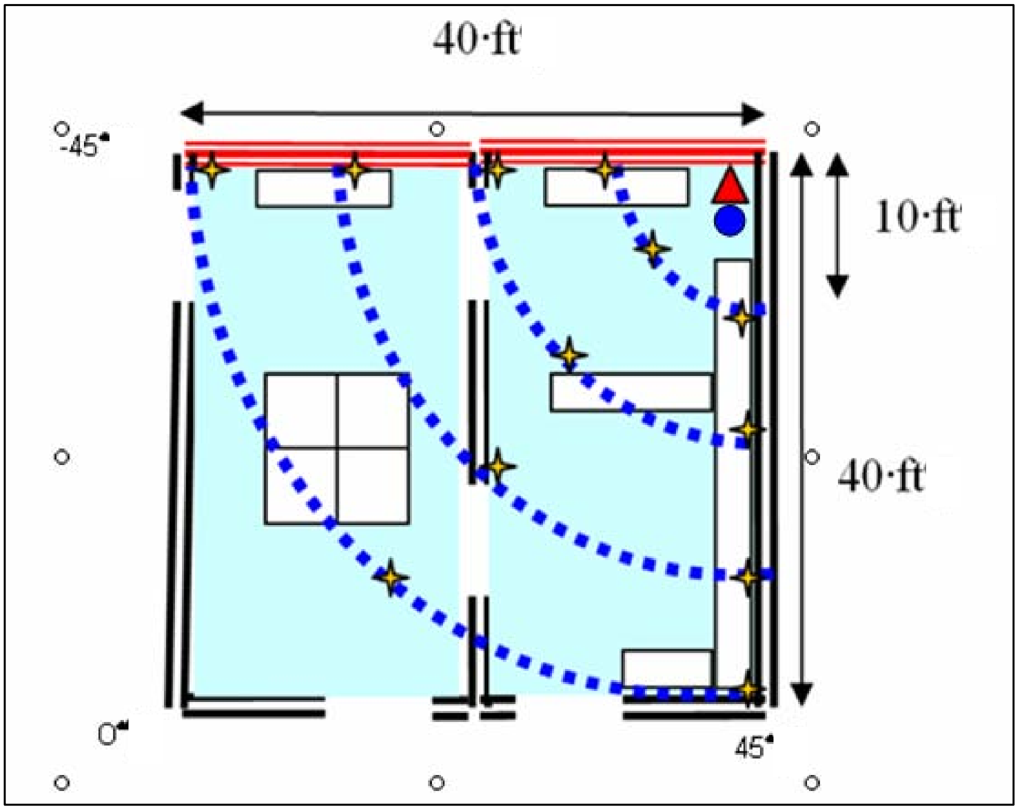

Figure 23. Layout of Spanagel Hall Rooms 3-13 and 3-15.

3. Outdoor Propagation

Similar to indoor propagation, measurements for outdoor propagation were carried out based on the layout as shown in Figure 20. The receive antenna and base station were placed on platforms that were 2.5 ft height above the ground and the transmit antenna was placed on a plastic clip board on the ground. Measurements were taken at incremental steps of 10 ft, and at every increment of 10 ft, measurements were taken at -45, 0 and 45 degrees. In Figure 24, the yellow star indicates the location of the transmit sensor, the blue circle indicates the location of the base station and the red triangle indicates the location of the receiving sensor spectrum analyzer. It was observed that there was also heavy attenuation as a result of the trees, grass and buildings surrounding the area. However, the path loss experienced in the outdoor

environment was marginally less than the path loss experienced from the indoor propagation as illustrated in Figure 24.

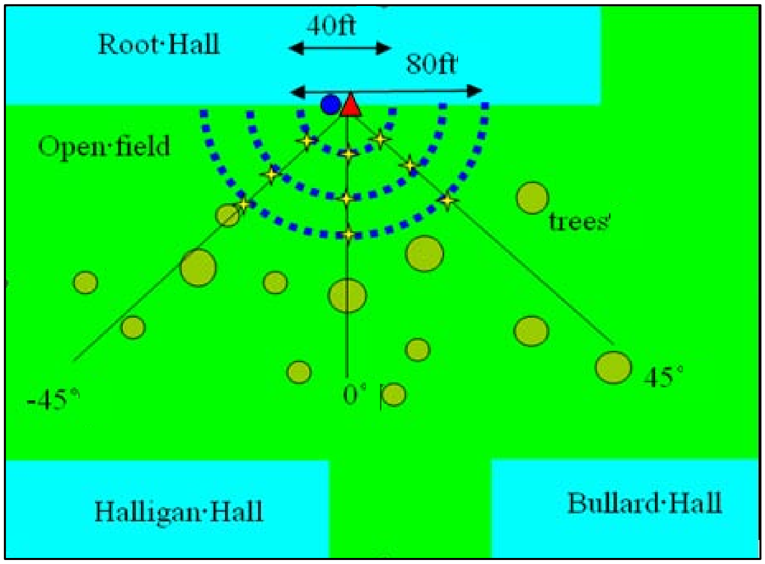

Figure 24. Layout of Open Field Area between Bullard, Root and Halligan Halls.

Based on the receive power measurements taken for all the three cases above, the path loss exponents of each case were derived and plotted as shown in Figure 25, which demonstrates the attenuation behavior of each of the four cases of propagation. As shown in this plot, the average values of the path loss exponents for indoor, outdoor, near free space (roof) and free space propagation are 2.9, 2.7, 2.1 and 2.0 respectively. The near free space average propagation path loss exponent of 2.1 is close to the ideal free space propagation path loss exponent of 2, thus showing that the Fresnel equation, as stated in Chapter II, has provided a close approximation of free space propagation. As for the indoor and outdoor propagation, the difference in path loss exponents is rather marginal, which could also be observed from the relatively close break distance of 40 ft and 70 ft, respectively.

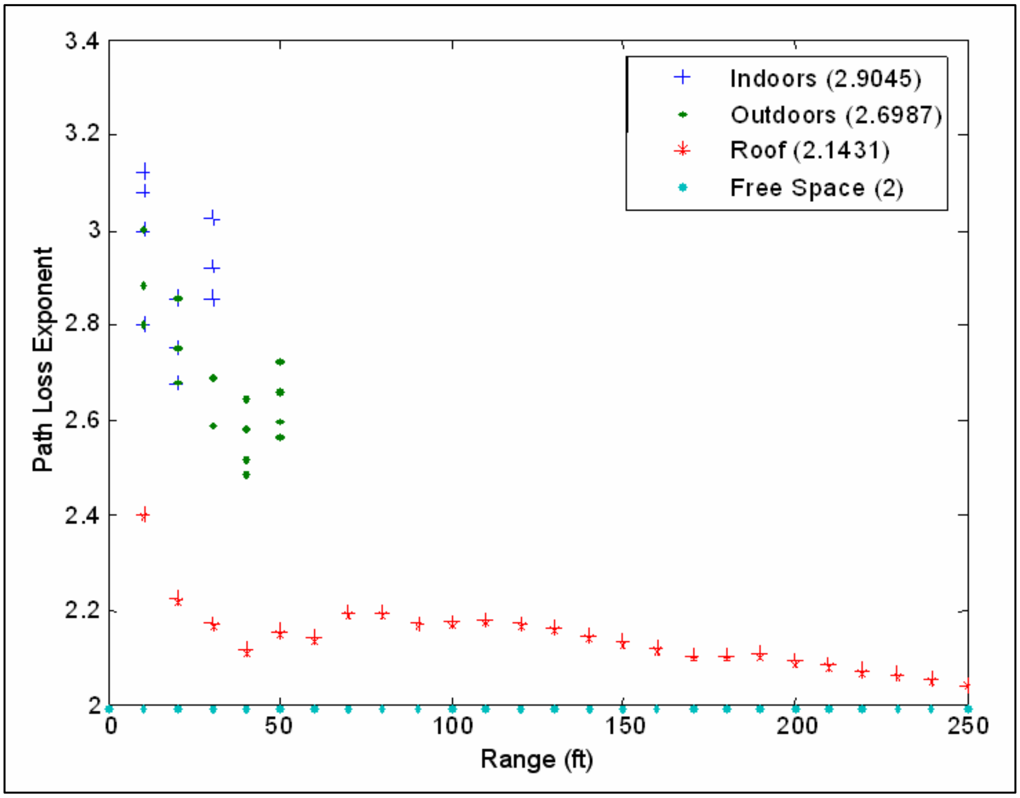

Figure 25. Path Loss Exponent vs. Range

For better clarity, path loss exponents are tabulated as shown in Table 2. This table summarizes the path loss exponent for the four cases, including that of ideal free space propagation. The range, mean and standard deviation of the path loss exponent is presented to provide a better feel of the exponent variation within each propagation model.

Path Loss Exponent (n)			
Model	**Range**	**Mean**	**Standard Deviation**
Free Space	**2**	**2**	**0**
Near Free Space	**2.0-2.4**	**2.14**	**0.07**
Outdoor	**2.5-3.0**	**2.7**	**0.12**
Indoor	**2.7-3.1**	**2.9**	**0.12**

Table 2. Path Loss Exponent.

B. BREAK AND RE-ASSOCIATE DISTANCE

Break and re-associate distance, with respect to the Mica-Z network sensor battery voltages, will be the last topic of discussion in this thesis. As highlighted in this thesis, extended network sensor battery life is critical to the operation of a wireless sensor network. This is especially true for cases where line power is not available or network sensors are deployed in any unrecoverable location. In addition, the cost and time required associated with changing the batteries for hundreds or thousands of sensors are unimaginable. In the case of the Mica-Z network sensor, two 1.5 V AA batteries connected in series were used to power the sensor. This is an incredibly small amount of power available to last a sensor for 1-3 years, which resulted in the demanding requirement of having network sensors to operate in low power and low data rate conditions. Even if the batteries can last for the long duration, it will be difficult to ensure that the batteries maintain constant voltage throughout their life span.

It is for the above reasons that there is a need to understand the relationship between the receive power against the battery voltage of the transmit network sensor so that a correction factor can be included in the design of a network sensor system to avoid disruptive failure of sensor network operation [21].

Measurement setup is based on near free space propagation as illustrated in Section IV-A-1. In this experiment, a DC power supply was used in place of the sensor batteries to provide the necessary power voltage to the network sensor. This approach provided flexibility in adjusting the supply voltage to the network sensor. After the voltage of the transmit sensor was set, the receive antenna was placed on the 2.5 ft high mobile platform and moved away from the transmit sensor, which was also placed on a 2.5 ft high platform, at incremental steps of 10 ft until a breakpoint was experience. After this, the receiving antenna was then moved towards the transmit sensor to determine the re-associate point and power. This procedure was repeated for voltage supply from 3.0 to 2.4 volts and the results are as shown in Figure 26. It illustrates the observation that the break

distance and re-associate distance decrease as the battery voltage decreases. This is not a surprising phenomenon as one would expect the power to drop when the battery voltage drops. The interesting observation here is the wide variation in break and re-associated distance when a small variation in the battery voltage was made. The relationship appears to be exponential for both cases. This is an important observation as it is not uncommon to have batteries with substantial fluctuating voltages, and such information will be necessary when deciding the type of batteries to be used for Mica-Z network sensor operation.

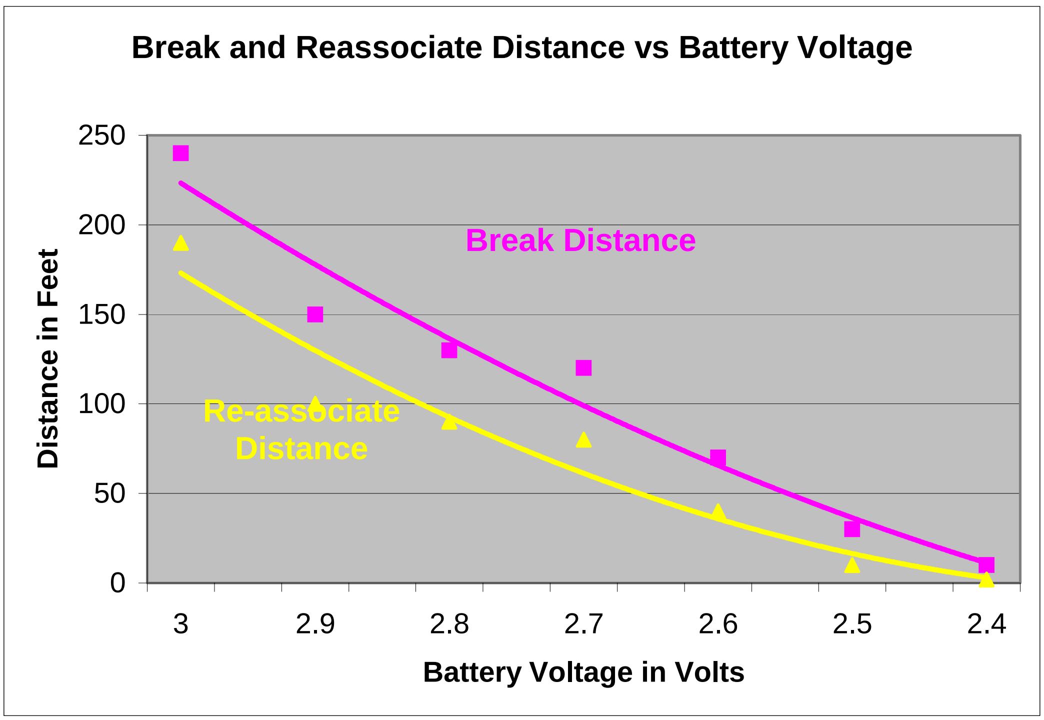

Figure 26. Battery Voltage vs. Break & Re-associate Distance.

In Figure 27, the relationship between break distance and re-associate distance to battery voltage is plotted in another dimension. The power and distance deviation between the break and re-associate points were plotted against the battery voltages. The purpose of this is to present the effects of battery voltage on the range and power performance. It was observed from the

plot that there is a diminishing effect on the break and re-associate distance variation as the battery voltage decreases.

No obvious functional relationship is observed on the power deviation plot as shown in Figure 27. However, it was observed that more power was required to get two sensors re-associated than causing a link break during the course of measurement. It was for this reason that re-association was re-established by bringing the Mica-Z network sensor closer to the base station when a link break was encountered. This is not very practical from a sensor network point of view as the actual situation will never allow anyone to do that. In order to avoid a situation of a network sensor not being able to re-associate back to the network, it is recommended that re-associate distance and power should be utilized as the basis of designing a reliable sensor network system.

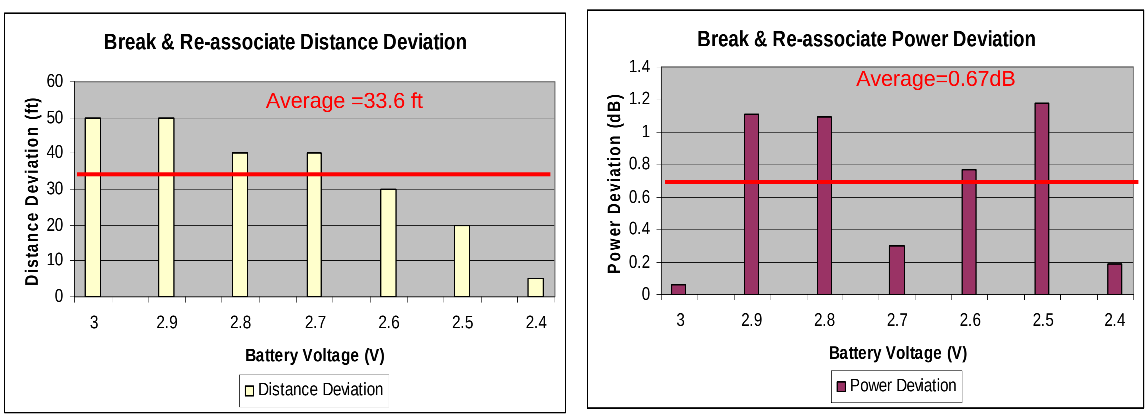

Figure 27. Break and Re-associate Deviations.

In this chapter, some of the Mica-Z power characteristics, such as the path loss exponent and effects of battery voltage on the operating range and receive power, were covered and discussed. Some important observations were also made to caution the network designers of the implicit effects that each of these characteristics may have on the performance of the Mica-Z network sensor.

V. CONCLUSIONS AND FUTURE RESEARCH

A. CONCLUSIONS

This thesis has highlighted the criticality of antenna and power characteristics in wireless sensor network design. The performance of the sensor network is highly dependent on antenna design, power source and operating environment and these characteristics can potentially cause total sensor network system failure if they are ignored. Based on the measurements carried out on the Mica-Z network sensor, it is concluded that the Mica-Z network sensor is a good potential candidate for many sensor network applications, but in actual deployment one needs to be aware of the limitations associated with the antenna design and RF power performance as discussed earlier. Therefore, it is essential that these characteristics are clearly understood and improved upon to deploy reliable Mica-Z sensor network.

In this thesis, two main parts of RF characteristics of the Mica-Z network sensor were analyzed and discussed. In the first part, VSWR, radiation pattern and antenna orientation were studied and discussed. Measurements were carried out and observations were made and presented to highlight the effects that the inherent Mica-Z antenna design has on the Mica-Z network sensor operation. Different ways were also explored, by means of using the GNEC modeling program, to model different antenna designs that could potentially be used to replace the existing Mica-Z antenna. Some interesting results were observed and it was found that each antenna model has its own virtues and is always application dependent. Although there is no conclusive evidence to decide the most suitable antenna to be used for the Mica-Z sensor network, the modeling gives an idea as to how the antenna design can be changed to help improve the performance of the overall sensor network design.

In the second part of the study, the power characteristics of the Mica-Z network sensor were observed in greater detail. The receive power measurements for near free space, indoor and outdoor conditions were taken

and evaluated. The path loss exponents for the three conditions were also derived to provide the user with a good feel of how the Mica-Z network sensor behaves electromagnetically under different environmental conditions. In the study of power characteristics, measurements on battery voltage against the operating range and power were also carried out to verify their relationship. The main highlight of this result is the high sensitivity of the operating range to the battery voltage, which may potentially cause major sensor network design discrepancies if not taken seriously.

The results presented and discussed in this thesis fulfill the primary objective of providing a fundamental understanding of antenna and RF power propagation characteristics of the Mica-Z network. Hopefully, networking enthusiasts will find these results useful in their design or research of the Mica-Z sensor network.

B. FUTURE RESEARCH

This thesis provides the fundamental understanding of Mica-Z network sensor mote which is critically dependent on power and the characteristics of the antenna used. More work in required is this area of research in order to provide a more comprehensive coverage of these aspects. One of the areas of research where future work can be focused is the modeling of the sensor mote antenna on a simulated plane that is close to the sensor mote circuit board. A preliminary model was created using a wire grid to simulate the ground plane created on the Mica-Z circuit board with a monopole antenna attached at one side of the simulated ground plane and the results are as shown in Figure 28.

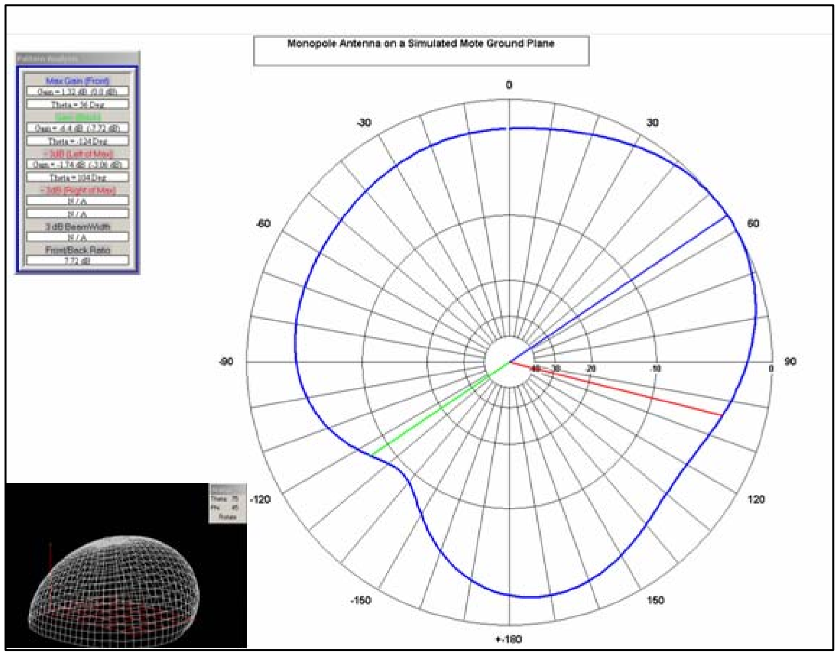

Figure 28. Monopole Antenna on a Simulated Mote Ground Plane.

Hopefully this will help to provide any future researchers an idea of how to approach their studies in the area of network sensor mote antenna characteristics.

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APPENDIX 1

```
CM 2.4 GHz Monopole for Crossbow Motes
GW 1 31 0 0 0 0 0 0.032 .0005
GE 0 -1 0
FR 0 1 0 0 2400 0
EX 0 1 1 0 1 0
RP 0 360 1 1000 0 90 1.00000 1.00000
RP 0 1 360 1000 90 0 1.00000 1.00000
EN
```

Appendix 1-A: GNEC Code for Monopole Antenna (Model 1)

```
CM 2.4 GHz End Loop Monopole for Crossbow Motes
GW 1 31 0 0 0 0 0 0.032 .0005
GW 2 1 0 0 0.032 0 -0.0015 0.0335 .0005
GW 3 1 0 -0.0015 0.0335 0 -0.0045 0.036 .0005
GW 4 1 0 -0.0045 0.036 0 -0.0065 0.03915 .0005
GW 5 1 0 -0.0065 0.03915 0 -0.0067 0.042 .0005
GW 6 1 0 -0.0067 0.042 0 -0.005 0.044 .0005
GW 7 1 0 -0.005 0.044 0 -0.003 0.045 .0005
GW 8 1 0 -0.003 0.045 0 0 0.045 .0005
GW 9 1 0 0 0.045 0 0.002 0.043 .0005
GW 10 1 0 0.002 0.043 0 0.002 0.04 .0005
GW 11 1 0 0.002 0.04 0 0 0.0365 0.0005
GE 1 -1 0
FR 0 1 0 0 2400 0
EX 0 1 1 0 1 0
RP 0 181 1 1000 -180 90 2.00000 1.00000
RP 0 1 360 1000 90 0 1.00000 1.00000
EN
```

Appendix 1-B: GNEC Code for End-Loop Monopole Antenna (Model 2)

```
CM  2.4 GHz Top Loaded Monopole for Crossbow Motes
GW 1 31 0 0 0 0 0 .032 .0005
GW 2 1 0 0 .032 0 .025 .032 .0005
GW 3 1 0 0 .032 0 -.025 .032 .0005
GW 4 1 0 0 .032 .025 0 .032 .0005
GW 5 1 0 0 .032 -.025 0 .032 .0005
GS 0 0 1.000000
GE 1 0 0
EX 0 1 1 0 1 0
FR 0 10 0 0 2000 100
RP 0 181 1 1000 -90 90 1.00000 1.00000 0
FR 0 10 0 0 2000 100
RP 0 1 361 1000 90 0 1 1
EN
```

Appendix 1-C: GNEC Code for Top-Loaded monopole Antenna (model 3)

```
CM  Turnstile dipole at 2.4 GHz
GW 1 61 -.03125 0 .01 .03125 0 .01 .0005
GW 2 61 0 -.03125 .012 0 .03125 .012 .0005
GS 0 0 1.000000
GE 1 0 0
EX 0 1 31 0 1 0
FR 0 1 0 0 2400 0
TL 1 31 2 31 50.00 0.263258      ! RG-174
RP 0 181 1 1000 -90 90 1.00000 1.00000
FR 0 1 0 0 2400 0
RP 0 1 361 1000 90 0 1.00000 1.00000
EN
```

Appendix 1-D: GNEC Code for Turnstile Monopole Antenna (model 4)

```
CM 2.4 GHz Monopole for Crossbow Motes
CM Mote ciruit board modeled as array
CM of wires on 1 cm spacing
GW 1 31 -0.015 0 0 -0.015 0 0.032 .0005
GW 2 3 .005 0.001 0 -.005 0.001 0 .0005
GM 20 6 0 0 0 0 .01 0 2 1 2 3
GW 3 3 -.005 .001 0 -.015 .001 0 .0005
GM 20 6 0 0 0 0 .01 0 3 1 3 3
GW 4 3 -.015 .001 0 -.025 .001 0 .0005
GM 20 6 0 0 0 0 .01 0 4 1 4 3
GW 5 3 -.025 .001 0 -.035 .001 0 .0005
GM 20 6 0 0 0 0 .01 0 5 1 5 3
GW 6 3 .005 .001 0 .005 .011 0 .0005
GM 20 5 0 0 0 0 .01 0 6 1 6 3
GM 20 4 0 0 0 -.01 0 0 6 1 6 3
GM 20 4 0 0 0 -.01 0 0 26 1 26 3
GM 20 4 0 0 0 -.01 0 0 46 1 46 3
GM 20 4 0 0 0 -.01 0 0 66 1 66 3
GM 20 4 0 0 0 -.01 0 0 86 1 86 3
GM 20 4 0 0 0 -.01 0 0 106 1 106 3
GE 0 -1 0
FR 0 1 0 0 2400 0
EX 0 1 1 0 1 0
RP 0 360 1 1000 0 90 1.00000 1.00000
RP 0 1 360 1000 90 0 1.00000 1.00000
EN
```

Appendix 1-E: GNEC Code for Monopole Antenna on a Simulated Mote Ground Plane

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